Dual-Tasking and Multiple Resources:

The Interference of Cognitive and Physical Demands in Real-World Applications

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By

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Abstract

Human Factors professionals regard Multiple Resource Theory (MRT) as a plausible explanation of the human cognitive processing system, but the theory lacks extensive testing with physical tasks. This is potentially a problem, because dual-tasking with cognitive and physically demanding tasks is a common requirement in high-risk settings such as military operations, firefighting, and search and rescue operations. Previous researchers utilized a verbal free recall task, a task demanding verbal processing resources, paired with a climbing task and reported dual-task interference. In the present work, the verbal free recall task was paired with a semantic discrimination task, a running task, and a spatial puzzle task. By holding one task constant amongst a variety of dual-task pairs, it becomes more feasible to analyze not only *how much* interference is occurring, but also *why*. The remaining five experiments pursued the overarching theme by utilizing a new verbal situation awareness (SA) task in place of the verbal free recall task. The SA task placed greater demands on episodic or narrative verbal memory more similar to real-world situations. The SA task was paired with the secondary tasks above, as well as a climbing task and a response inhibition task. It was found that the specific resources required, as well as the executive resource requirement (e.g. manipulation, planning) of a task both contribute to the dual-task interference. Climbing required resources beyond the scope and nature of what would be expected according to the MRT; the total dual-task inference for this task exceeded the interference for the other task pairs. In order to better avoid dangerous dual-tasking situations and to provide appropriate aid if those situations cannot be avoided, assessing both the specific *and* general resource demands of any physically and cognitively challenging task that might be required in high-risk operations is critical.

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1 Introduction

It can be difficult to do two or more activities at once, even if they are quite easy individually. Executing multiple tasks simultaneously can be detrimental to performance on one, some, or all of the required tasks. Unfortunately, multi-tasking is an inescapable reality in the modern era. The co-occurrence of multi-modal requirements pervades many different realms, from driving, athletic competitions, and military operations to productivity interventions in the workplace. Even the use of "smart" devices intending to augment performance can cause cognitive processing interference and overload, as the information these devices present may divert attention and limited processing resources away from the primary objective. Understanding how different tasks interfere with each other, and ways this interference can be diminished is critical. Though it is known, in general, that people are poor multi-taskers, the human cognitive resource structure is still not completely clear. The purpose of this research is to contribute to the body of knowledge that may improve the safety, efficiency, and overall performance on tasks in real-world multi-tasking scenarios.

Wickens' (2002, 2008) Multiple Resource Theory (MRT) is a common explanation for why dual-tasking performance impairments may occur to a different extent under different circumstances. This theoretical perspective will be used as the primary foundation for the present research, but it will be critically evaluated along the way, and presented alongside alternative or complementary explanations. While the MRT is generally accepted, it has yet to be systematically tested and the cognitive resource structure thoroughly understood. For example, two tasks that do not seem to overlap on any of Wickens' dimensions can still interfere with each other. This interference cannot be fully explained by his model, unless one considers a general resource overload or executive processing bottleneck.

Dual-task experiments that hold one task constant among a variety of secondary tasks provide a useful framework for exploring the MRT and the effects of different specific resource demands. Many dual-task psychology studies have used simple activities such as finger tapping or verbal suppression while doing various other tasks simultaneously, but less research has been done on more realistic and complex physically demanding tasks that might be expected in high risk operations. The exercise science community has also extensively explored the interaction between many physical and cognitive tasks, providing an additional body of work to that of laboratory cognitive psychology. Mental fatigue has been shown to impair physical performance (Marcora, Staiano, & Manning, 2009), physical fatigue can impair certain types of mental performance (Dietrich & Sparling, 2004; Labelle, Bosquet, Mekary, & Bherer, 2013), and there have also been beneficial cognitive effects found (e.g., a review by Lambourne & Tomporowski (2010) found that simple choice and discriminant reaction time task performance generally improved during steady-state aerobic exercise) . Unfortunately, the majority of the exercise science experiments use rather artificial tasks such as treadmill running, walking, and stationary cycling, which require minimal cognitive resources. A gap therefore exists between the available research and reality. Both the exercise science and basic cognitive psychology experiments generally fail to look at how the resource theories apply to real-world problems, where the demands of both the physical and mental activities will likely require greater and more diverse resources. For example, it is much harder, both mentally and physically, to run on a trail with obstacles and uneven terrain or through an urban environment with traffic, like an army scout or police officer might have to do, than on a treadmill (Blakely, Kemp, & Helton, 2016; Whelan, 1996). In addition, the person performing the physical task often has to simultaneously self-pace, navigate, calculate, or communicate with remote team members. In these situations, greater interference is expected, and it is important to understand whether it is due to physical demand, spatial demand, other resources, or perhaps a drain on the general resource pool and/or a processing bottleneck. One purpose of this dissertation is to begin linking and building upon the foundations of cognitive psychology and exercise science to make more applicable predictions or interventions, by approaching the same questions in more realistic situations using human factors methodology.

There have been several relevant theories regarding the human cognitive resource structure. Kahneman's foundational perspective that a unitary, limited, and renewable pool of resources are available for attention, along with Wickens' Multiple Resource Theory will be discussed. In addition, while memory itself is not a primary investigative aim of this dissertation, working memory theory must also be considered when approaching any research on the cognitive resource structure. Finally, the present state of the dual-tasking research in the exercise science community will be considered.

1.1 Attention and Information Processing

People are generally good at directing their attention to stimuli of interest and blocking out distractions. Without the ability to focus attention, people would learn and accomplish very little in life (Stroh, 1971). Unfortunately, similar to physical energy, humans seem to have a limited supply of the mental energy that enables them to successfully complete cognitive tasks. For many years, scientists have studied the limits of attention that constrain performance when multi-tasking. Kahneman states that attention (and its division) is "one of the classic dilemmas of psychology" (Kahneman, 1973, p. 5).

Theories of attention can be classified into three categories: filter (bottleneck), general resource capacity, and multiple resource theories. Alternatively, the theories can also be classified into structural versus capacity (or effort) models. Models in different categories often predict similar interference, but usually for different reasons. Structural theories cite incompatible or simultaneous demands as the problem, while effort or resource theories cite a limited mental capacity to explain interference

(Kahneman, 1973). The key to finding support for one model over another is to find an experimental paradigm for which the different theories would make different dual-task performance predictions.

The bottleneck or filter theory of attention, a structural model, suggests that breakdowns in performing multiple simultaneous tasks result primarily from the serial nature of the human information processing system. A stimulus must be perceived and then identified before a response is then selected, prepared, and administered, and a bottleneck could exist at various points throughout this process. Thus, if multiple attention requirements exist at once, not all items may make it through the attention filter, even if the tasks are not very demanding. The filter theory predicts interference when simultaneous, incompatible tasks require processing by the same mechanism at the same time (Cowan, 1995; Kahneman, 1973).

Broadbent's filter theory (1957) suggested that the bottleneck occurs in the very first stage of perceiving stimuli – in other words, if two stimuli are presented, only one can be processed at a time. Deutsch and Deutsch (1963) and Welford's later single-channel theory (1967), on the other hand, suggested that the bottleneck occurs at the response selection stage: people perceive and process the simultaneous information, but can only respond to one thing at a time. Thus, listening for a specific cue in *either* ear is possible, while Broadbent's original theory would say it is not. An additional filter theory expanded upon Broadbent's original model but focused more on the nature of the control processes that transferred information amongst the various stores (Atkinson & Shiffrin, 1968). Treisman's filter attenuation theory suggested that it is more difficult to discriminate stimuli if items are rejected by the filter (Treisman, 1960), and Treisman and Riley (1969) later discovered an effect of channel bias for detecting significant targets. Evidence that concurrent monitoring tasks in the same modality are more difficult than in different modalities provides additional support for structural interference (Treisman & Davies, 1973).

The theories in this category generally fall short, however, in explaining reaction time evidence and certain types of interference (or lack thereof). This suggests the human information processing system is far too complex to be explained merely by a filter (Kahneman, 1973). For example, it was found that information from an ignored conversation can still be processed in tandem with the conversation of focus if there is a salient cue in the ignored channel (Moray, 1959). Though selective attention is quite effective, focusing attention on one stimulus may not completely prevent the processing of other stimuli on irrelevant or even actively ignored channels (Kahneman, 1973). Enough evidence exists for the processing of ignored information to ultimately discount the filter theory in favor of the resource theory.

Though the resource perspective has been widely supported over filter theories for decades, there is still some debate as to the specific cognitive resource structure, and how this structure plays a role in exacerbating or mitigating dual-task interference. Do resources come from a common pool, with performance breakdowns resulting primarily from the overall amount of resources required versus those available? Or, alternatively, do different tasks draw from different resources, where tasks using similar resources will interfere more than tasks requiring dissimilar resources? First the perspective of a general or unitary resource capacity model is discussed, and this is followed by a discussion of the multiple resource theory of human cognition.

1.1.1 The Central Capacity Model of Attention

A general, unitary resource theory (or central capacity interference model; Navon & Gopher, 1979) suggests that there is one general pool of cognitive resources, limited yet renewable, which is used to attend to, process, and respond to relevant environmental information. Thus, performance breakdowns are not due to structural bottlenecks proposed by the filter theories, but the overarching limit on the human capacity for mental work (Kahneman, 1973). The main assumption is that performance falters if the amount of attention or effort allocated, which is dependent on the amount available, falls short of the amount of attention demanded by a given task or tasks. It is also believed that the limited capacity can be allocated freely among different task demands (Kahneman, 1973; Moray, 1967). The amount of attention allocated will also rise as demand rises, but this can only be done to the extent that there are resources available. Therefore, when a task becomes more complex or difficult, performance will eventually decline despite the increased effort (Kahneman, 1973).

Moray (1959) discovered that people have the ability to shift their attention to an unattended channel when they hear their name spoken in that channel, which inherently means that other channels can, in fact, be processed simultaneously – a direct contradiction of the early filter theories. Building from this discovery and others, Kahneman (1973) revolutionized the way human information processing is understood. Though he does not discount the importance of the cognitive structure, Kahneman shifts the focus from a strictly structural model to a capacity model to explain dual-task interference.

The term "resource" itself was coined by Norman and Bobrow (1975); they suggested that all tasks require some level of mental effort, resources, attention, or capacity – relatively synonymous terms for the current metaphorical construct of interest. The term resource has been preferable over the others, however, because 'capacity' suggests a specific limit, 'attention' has many different meanings, and 'effort' has to do with motivation which doesn't always have to correlate with the commodity that enables performance (Wickens, 1981). These resources are limited, yet renewable. Even one simple task, over time, can exhaust the available resources. Therefore, if several tasks are competing for resources, performance may deteriorate even faster. The ability to multi-task is entirely dependent on the amount of resources required by each task and a person's capacity available at a given time. Kahneman (1973) suggested that the capacity is flexible and varies due to environmental factors, the tasks at hand, and the individual's condition (e.g., arousal or expertise).

The resource theory has been supported by extensive physiological evidence. Two common indicators are cerebral oxygenation, detected in the frontal lobe by near-infrared spectroscopy (NIRS), and cerebral blood flow velocity (CBFV), detected in the middle cerebral artery by transcranial Doppler (TCD) sonography (Funke et al., 2012; Shaw et al., 2009, 2013; Warm & Parasuraman, 2009). Cognitive processing requires oxygenation, and such processing also creates byproducts (e.g., carbon dioxide). The increase in byproducts leads to increased blood flow to remove the waste products. A decline in oxygenation or blood flow has been shown to correlate with performance decline on cognitive tasks, and is therefore viewed as indicative of overtaxed resources and resource depletion (Aaslid, 1986).

Complementary to a unitary resource perspective, it has been suggested that as the number of tasks increases, the difficulty of performing those same tasks also increases, due to a procedural bottleneck effect (Pashler, 1994). Performance degradation is observed once the available resources fail to meet the resource demand, and this process inherently occurs faster when dealing with a greater number of tasks simultaneously.

Kahneman (1973) and Treisman (1969) would agree that different types of attention are governed by different mechanisms and rules, though Kahneman approaches the problem from a capacity perspective and Treisman from a structural perspective. For example, tasks can be classified based on the source of inputs, type of targets, attributes of objects, and category of responses, but from the central capacity model, overlap of attributes or categories are not the primary causes of interference. Unlike a structural model, interference from a central capacity perspective is primarily nonspecific. When it comes to the resource requirement, the question 'how much?' is far more important than 'what type?'

Kahneman (1973) suggested that dual-tasking success depends first and foremost on the amount of attention resources available to devote to the tasks at hand, and how many resources those tasks actually require. The allocation of resources is also important. Is the operator aiming to do both tasks equally, or complete one task fully and devote any leftover resources to the other? Is there anything particularly novel or meaningful to attract attention to one of the tasks? Has the operator been given any instructions on prioritization? The capacity theory must deal with questions of what makes a task more or less demanding, what factors control the available capacity at a given time (e.g., arousal), and what rules dictate the allocation of resources (Kahneman, 1973). An assumption of resource theory is that the cognitive system is able to allocate resources selectively and freely (Navon & Gopher, 1979). Though the system does not necessarily work consciously, and is not always able to place precise levels of emphasis on different tasks (Kahneman 1973), there is generally a certain level of voluntary control of attention (Navon & Gopher, 1979).

Navon and Gopher (1979) explained the resource perspective of the cognitive processing system, and resulting performance, in economic terms. The finite processing power (i.e., resources, capacity, attention, etc.) is the supply, while the resource requirement or difficulty of a given task is the demand. Supply and demand in free markets determine the price of goods, while the supply and demand of cognitive resources determine how well a person performs a given task (Navon & Gopher, 1979). The framework becomes more complex when considering multiple tasks, as available resources must now be divided, and required resources have likely increased. Resources are allocated based not only on the relative demands of each task, but also based on individual preferences. Resources are not always evenly or consistently split between tasks, and sometimes the loss of performance by sacrificing resources in one task will not provide an equivalent gain in the other task (Navon & Gopher, 1979).

Capacity is limited, varies with arousal level, and is influenced by the momentary demands of activities. A rise in demand can increase arousal, effort, and attention (Kahneman, 1973). Not only do variations in attention demands influence arousal, but variations in arousal also affect the way that attention is allocated. It has been suggested that people are able to mobilize more resources with higher task demand and arousal, and thus simply can't try as hard on an easy task as they can on a somewhat harder one. The Yerkes-Dodson Law (Yerkes & Dodson, 1908) states that performance is optimal at an intermediate level of arousal, and improving performance on a simple task requires more arousal than on a complex task. Studies of performance and physiological arousal have shown that at an intermediate difficulty, participants will make errors, even though they are still able to increase their effort as the difficulty increases. Though the choice to work is voluntary, how *hard* people work may be more dependent on the task demands than their conscious control (Kahneman, 1973). Unfortunately, multiple task demands may increase arousal and effort, but that increased activation of the sympathetic nervous system narrows the focus, making it all the more difficult to divide attention - even if task demands are well below the available capacity (Brisswalter, René, Audiffren, & Delignieres, 1997; Tomporowski & Ellis, 1986). If load is low, on the other hand, there may be no interference at all (Kahneman, 1973). The decrement from increased arousal occurs much sooner in complex (or multiple) tasks than simple ones. When operating under low arousal, there is generally broad focus and low selectivity, meaning people are more likely to accept irrelevant cues (or make false alarms). However, as arousal goes up, focus becomes more selective, helping people reject more irrelevant cues. If arousal increases beyond the optimal zone, the range of possible cues continues to be restricted, leading to missing relevant cues and a deterioration of performance. Assuming that the range of cues for a simple task is inherently narrower to begin with than for complex tasks, the optimal level of arousal for the best possible performance is higher for simple than complex tasks, though both follow the inverse U-shape (Bahrick, Fitts, & Rankin, 1952).

Simply put, high arousal leads to focusing on the most salient or important aspects of a situation at the expense of others (Kahneman, 1973). Because more complex tasks usually more division of attention, performance suffers more than in simple tasks where a narrowing of attention is often beneficial. This difference is parallel to that of optimal arousal for automated or easy versus new or difficult tasks. Unfortunately, even with simple tasks, an increased tendency to focus on a few important cues is also accompanied by a decreased ability to discriminate between the relevant cues and others, consequently resulting in a decreased ability to focus on the relevant cues. People may become more selective, but not necessarily more effective if fine discrimination is required (Kahneman, 1973).

Momentary effort and total work required must also be differentiated – Kahneman (1973) used the metaphor of the difference between a hundred yard sprint and a long walk. When considering the effects of capacity availability and requirements, one must take into account how the time pressure of a task influences the mechanism – is a sustained task that requires thoughtful planning but little time pressure as interfering as a memory task that requires active rehearsal of a list but little thoughtfulness? The majority of mental work resembles the sustained, but low momentary effort processes – no substantial exertion is required, but mistakes are still made and fatigue sets in over time. The addition of time pressure inherently imposes a greater load on working memory and requires more of the available attentional capacity in the short term.

As resource demand increases, a decrease in the efficiency of using those resources for performance typically occurs. Completely inefficient processes (i.e., changes in resources don't affect performance) are called data-limited processes (Norman & Bobrow, 1975). Alternatively, if efficiency is not zero, a process is resource-limited. If two tasks are being performed at once, and there is a desire to divert resources from one task to the other, this will not necessarily result in a 1:1 performance change. For example, taking resources from one task may hurt performance on that task far more than it will help performance on the second task. In other words, tasks can have different *sensitivities to resources* (Navon & Gopher, 1979). These analyses of performance trade-offs are all based on the assumption of central capacity interference, or a general pool of cognitive resources.

So far, primarily the demand side of dual-tasking performance patterns has been discussed. However, the supply of resources available is also important. Resource theorists – whether coming from a multiple or unitary perspective - agree that people have a limited set of renewable mental resources. However, the amount of resources at any given time is hard to pinpoint, as capacity can fluctuate between and within people for different reasons (Kahneman, 1973). Arousal, for example, can enable access to more resources than the baseline level, just as a physical threat can arouse individuals, via the sympathetic nervous system, to acts of strength and speed that are beyond what that person can typically achieve. Kahneman suggests that capacity is elastic: additional load induces arousal, which in turn mobilizes resources and stretches capacity to accommodate the greater load. This even makes it possible for performance on a task to improve beyond its single task limit if a second task is imposed. It should be noted though, that while capacity can stretch, it cannot do so without limit. In strict terms, capacity is the stable level of resources able to be supplied under heavy load, not temporary bursts caused by any number of factors (Navon & Gopher, 1979).

A concurrence benefit, where the demand of two tasks together is less than the sum of their individual demands, is also possible when dual-tasking. This is also called dual-task integrality (Kramer, Wickens, & Donchin, 1985). From a unitary resource perspective, it can be difficult to explain why performance on at least one of the tasks would *improve* when performed concurrently with another task. Navon and Gopher (1979) explained, however, that task redundancies, context effects, priming, and various other reasons might lead to this facilitation effect. An example is that if someone is required to estimate the distance of two remote targets, the same distance cues could be used for each, lessening the mental computation required for the second target. In addition, foot tapping can be helpful for playing a musical instrument (Navon & Gopher, 1979). The possibility of concurrence benefits is important to keep in mind when interpreting dual-task performance patterns. Kramer and colleagues (1985) found evidence for a dual-task concurrence benefit and their task integration hypothesis in the improvement of participants' tracking performance when performing a secondary discrimination task that required processing of relevant information to the primary task. In other words, a correlation between task requirements enabled the tasks to function as a unit and therefore result in task redundancy benefits.

Even from a central resource capacity perspective, many theorists recognize that tasks can also interfere with each other structurally. The joint demand of two tasks *can* be greater than the sum of their individual demands (Kahneman, 1973). Navon and Gopher (1979) call this a concurrence cost, and it happens when certain elements of one task actively interfere with performance in the other task. An example of this is the classic Stroop interference task (Stroop, 1935). Reading words or stating the color that a word is written in, in isolation, impose little resource demand. However, it is necessary to actively inhibit one in order to perform the other in the Stroop task (Navon & Gopher, 1979). Because reading is automatic, it is actually very difficult to vocalize the ink color of a word when the word is the name of a different color. Additional reasons for concurrence costs in certain circumstances are the higher order processes such as planning, coordinating, and active assigning of resources that may be necessary in order to perform certain tasks together. These "management" processes require resources in and of themselves (Navon & Gopher, 1979). "Because of the possibility of a concurrence cost, one should be cautious in interpreting performance decrements from single- to dual-task situations as representing capacity interference." (Navon & Gopher, 1979).

Because there are several possible reasons for interference, beyond that of mere supply and demand, many performance decrements observed from single- to dual-task cannot be fully attributed to capacity interference without further evidence (Navon & Gopher, 1979). However, if it is demonstrated that performance on one task can only improve at the expense of another, it is likely the tasks compete for the same resources. Unfortunately, research has not been traditionally designed to allow for clear observation of such performance trade-offs. Often, rather, the difficulty level of one task is varied and the performance on the other task is examined. If a task is more difficult, it hypothetically consumes more resources which would therefore have to be diverted from the second (non-manipulated) task. However, this methodology is flawed, as the preferences of the operator may interfere with the intended resource allocation, as well as other interaction effects (Navon & Gopher, 1979). Due to the restrictions in both performing and interpreting research on the central capacity interference models, the multiple resource perspective will now be discussed.

1.1.2 The Multiple Resource Model of Attention

An alternate perspective to central capacity models are multiple resource models. The multiple resource perspective carries forward the assumption that there are limited mental resources available for attention, processing, and responding. However, it rejects the idea of one general, undifferentiated resource pool and suggests, rather, that there are several independent resource pools from which different types of task demands draw. Though all types of resources are limited, utilizing one specific type of resource should not, according to this theory, deplete the resources available in a different pool. It recognizes the importance of both structure *and* capacity. If tasks require dissimilar sensory inputs, response outputs, or type of memory code, they are more likely to be successfully executed in tandem (Wickens, 2002).

Allport, Antonis, and Reynolds (1972) suggested that all interference between tasks might be linked back to a structural cause. The human cognitive structure is not just a simple, all-purpose processing system. It would be better described as a variety of linked but independently operating systems with special purposes and abilities. As evidence, Allport and colleagues (1972) showed that remembering a list is more difficult when shadowing an auditory message than visual message, particularly if the message is made up of words compared to pictures. In other words, though the general demand of each task shouldn't change across structural modalities, dual-tasking within modalities is more difficult than dual-tasking across modalities.

A general capacity perspective assumes, by definition, that the demands of two tasks are additive. However, there is plenty of evidence that the demand of joint performance can exceed the sum of the separate demands. Careful research design can tease out whether interference comes from capacity problems, structural problems, or both. For example, if tasks A and B are equally difficult when performed alone, and if task A performed simultaneously with task C is more demanding than the simultaneous performance of task B with C, some of the A-C interference must be due to a structural, rather than purely capacity, cause (Treisman & Davies, 1973).

The difference between the simple sum of demands and the actual observed demand is thus attributed to structural interference. If two tasks are incompatible for whatever reason, the effort to complete both at once is greater than the sum of the effort to perform them separately. Any such interaction between tasks is an argument against the general resource perspective, because this inherently means that the task demands are not simply additive. Knowing a mere *quantity* of demand of each task cannot be used to predict the amount of interference between the tasks. However, task difficulty is still important, in conjunction with specific resource overlap, in understanding the interference. Though difficulty plays an important role, for example one might be able to perform two easy tasks in tandem with greater accuracy than two difficult tasks, it is particularly important to consider the structural, in addition to capacity interference. Kahneman (1973) suggested that the label ‘structural interference’ should be used when the interference is primarily caused by the interaction between the tasks, whereas ‘capacity interference’ should be used when the difficulty of the tasks is to blame. However, the multiple resource perspective generally recognizes that both structure and capacity are crucial in understanding interference effects.

A multiple resource perspective was suggested as an alternative to the general resource capacity perspective by Norman and Bobrow in 1975. Rather than choosing a strict structural model or capacity model, neither of which can account for all performance results found in the literature, a multiple resource perspective suggested the attentional resource structure is a complex combination of the two. Both qualitative and quantitative information are important in understanding the cognitive processing system. Resources are not homogenous, as previously believed, and different tasks utilize different compositions of resources – both the existence of specific demands (i.e., structure) and their quantitative nature (i.e., capacity) are relevant (Navon & Gopher, 1979). Two tasks can be incompatible because they share common structural components, and/or because they compete for access to a single central processor. There have been single channel theories of processing (i.e., a processing bottleneck; Welford, 1952), single capacity theories (Kahneman 1973), multiple channel theories (i.e., people can process audio and visual input simultaneously but the resources required come from the same place), and now the multiple resource perspective suggests there are both multiple channels and multiple capacities.

If the cognitive processor has multiple resources at its disposal and two tasks require completely distinct resources, the tasks should be able to be performed simultaneously without performance decline. Downgrading performance on one task in order to release resources towards the second task would provide no benefit to the second task, as those resources would not be relevant. There is therefore no reason to downgrade performance on the first task. However, if both tasks use the same resources, there would be a performance trade-off as the brain attempts to optimize the use of resources between the two tasks. If tasks require some common resources but also some independent resources, there will not be a

1:1 trade-off between performance loss in one task and performance gain in the other, as some (but not all) of the resources released will be efficiently utilized in the second task. In this case, manipulating the difficulty of one task may not affect performance on the other task. However, if the unique resources are not at an optimal level, performance may not even improve with the release of the common resources from the other task, as the proper ratio of both resources are needed for successful performance (Navon & Gopher, 1979). The concept of diminishing returns is also thought to apply to resource utilization. In other words, beyond the optimal level of resources required, adding additional resources will not continue to improve performance (Navon & Gopher, 1979). Practice, however, may improve dual-tasking performance if one or both tasks become increasingly automated (i.e., require fewer resources/less attention), or if a person becomes more accustomed to performing them together and integrates them into a singular task entity. This entity will still require all of the different resource components, but there will be less interference overall as attention is more effectively shared among them. The converse can happen as well – excess interference can occur due to the mere organization, or executive or planning effort that it takes to complete the tasks simultaneously (Kahneman, 1973).

Various specific models have been suggested to explain the way resources are divided and utilized. Schneider and Detweiler's (as cited in Cowan, 1988, p.33) model of memory/attention is particularly complex, including eight separate modules for visual, auditory, speech, lexical, semantic, motor, mood, and context processing. Cowan (1988) was not committed to this particular breakdown, but it is relatively plausible. One of the more thoroughly developed and well accepted models of human cognition is Wickens' Multiple Resource Theory (MRT), which allows for prediction of when tasks can be performed together successfully, when they will interfere, and when task difficulty fluctuations will result in performance tradeoffs (Wickens, 1981, 1984) . The type and extent of interference between tasks, according to Wickens (2002), depends on the overlap of the tasks on four possible parameters: stage of processing (perception, cognition, or response), sensory modality (visual, auditory, or other), code of processing (spatial or symbolic), and focal versus ambient focal view. Wickens' proposed structure can be visualized in Figure 1-1. The more similar two or more tasks are along any of these parameters, the more difficult it is to effectively share attention between them because those specific resources are overtaxed. For example, one cannot listen to a story successfully while reading another (Kahneman, 1973), but it is plausible that one could listen and comprehend a story while working on some sort of visual-spatial problem. Though the multiple resource perspective brings structural issues to the forefront, the total resource demand of each task is also required in order to predict interference between tasks (Wickens, 2002,2008).

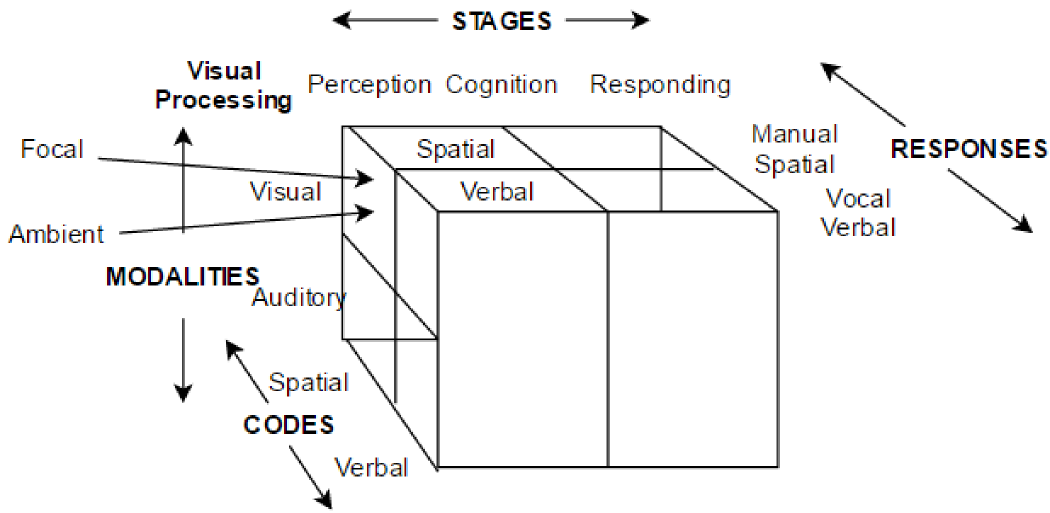

Figure 1-1. A drawing of Wickens' 4-D Multiple Resource Model.

Wickens suggests that his 4-dimensional model could serve to predict the level of performance on two time-shared tasks (Wickens, 2002). He also recognized the inherent "cost of concurrence," or executive demand, present in any time sharing and division of attention, regardless of individual task demands (Navon & Gopher, 1979; Wickens, 2002). Wickens created a conflict matrix allowing for predictions of the relative interference of two tasks given their resource demand plus an assumed baseline conflict value (Wickens, 2002). The matrix is useful for assessing many real world designs, from multi-modal communication options for military operators (e.g., a choice of text, radio, or combination depending on the situation and other tasks at hand), to computer or vehicle interfaces (Horrey & Wickens, 2004), voice-control applications on cell phones, and others.

Though the 4-D model is relatively intuitive, the computation on Wickens' conflict matrix involves several steps. Tasks must be coded for each resource used depending on task characteristics and difficulty. A score of zero would imply that the task doesn't use a certain resource, and the value increases as the presence of the resource demand plus difficulty of the task increases. A demand vector of three numbers results for each task, as the task is coded for stage, code, and modality. Then, the three numbers in the vector are added to come up with the demand scalar. When dual-tasking, the demand scalar from both tasks are added together to come up with the total demand score. This number is then transformed to fall in the range of zero (easiest task combination) to one (most challenging task combination). How much conflict there is at each specific resource is also assessed, resulting in a matrix of 36 resource-conflict scores. The total interference score is then calculated as the sum of the total demand score and the resource-conflict score, which reflects both the presence of structural interference (specific resource competition) and task difficulty. See Wickens (2002) and Horrey and Wickens (2003) for further explanation. The computation matrix has been shown to predict performance decrements in different dual-task combinations, but it requires some expertise and an in-depth knowledge of task demands, and cannot predict actual performance loss – only relative interference (Horrey & Wickens, 2003).

The MRT has been supported by several dual-task studies which showed that it was easier to concurrently perform two tasks if they did not require overlapping resources (Brill, Gilson, & Mouloua, 2007; Brill, Mouloua, Gilson, Rinalducci, & Kennedy, 2008; Brill, Mouloua, & Hendricks, 2009; Caggiano & Parasuraman, 2004; Helton & Russell, 2011b, 2013, 2015). The MRT has also been applied in the field of healthcare research, where multi-tasking and high mental workload are common and a failure to keep up with task demands is dangerous. The MRT can provide insight into the importance of experience and thus automaticity when multi-tasking in surgery, as well as the role of tactile versus visual information processing in laparoscopic and traditional surgery (Douglas, Raban, Walter, & Westbrook, 2017; Zheng, Cassera, Martinec, Spaun, & Swanström, 2010).

Another common application of the MRT is in the study of driver distraction, particular regarding cell phone usage. A meta-analysis revealed that there is a definite cost to driving performance, particularly reaction time tasks, when drivers are engaged in cell phone conversations – even when hands-free phones were used. Costs to lane-keeping, alternatively, were much smaller (Horrey & Wickens, 2006). The researchers suggested that reactions to hazards and lane-keeping may be differentially impacted by cell phone conversations because they require different resources (ambient versus focal vision) on the MRT model. They also suggested that lane-keeping is a more automated task, meaning it requires fewer resources overall. Cell phone usage thus may interfere more with reaction to hazards at the processing stage (i.e. response selection or decision making). This suggestion is further supported by the finding that the costs to driving were similar if the cell phone was hands-free, meaning it is the cognitive rather than the manual aspect of the phone conversation causing the interference (Horrey & Wickens, 2006).

While the MRT has been frequently cited in the literature, few of the specifics have been systematically tested. The MRT makes sense in regards to known functions of physically differentiable brain processes (e.g., speech and motor activity are generally controlled by frontal brain regions, while perceptual and language comprehension tends to occur in regions posterior to the central sulcus, verbal processing is generally believed to occur in the left hemisphere and spatial processing in the right, and visual and auditory processing occur in separate distinct brain regions; Friedman, Polson, & Dafoe, 1988; Wickens, 2002), but unfortunately, most tasks cannot be easily classified into such black and white structural dichotomies. For example, a working memory task developed to use spatial resources may also have a symbolic or verbal component, and a task that seems purely physical may require planning or an internal monologue. Tasks that do have a physical component may have their resource demand underestimated, as Wickens did not include physical demand in his conflict matrix. The characteristics of each task must be thoroughly examined to predict the amount of interference. Then, in addition to the type(s) of cognitive resources, one must consider the amount of resources demanded from individual resource pools, as well as the executive demand required to perform both tasks at once (Wickens & McCarley, 2008).

A multiple resource perspective is a prominent theoretical framework for cognitive processing because although it is not perfect, it requires fewer caveats to explain the majority of research findings than does the strict central capacity framework. It can usually account for performance findings that cannot be explained by either structural or central capacity models alone. However, the MRT requires further testing. For example, it was found that talking on a hands-free cell phone while driving could still distract operators from the primary driving objective (Strayer & Drews, 2007), even though the resources required did not explicitly overlap on Wickens' model. Emerging research, particularly in the applied physical domain, suggests that some caveats to the MRT model are still required to explain certain types of interference (Darling & Helton, 2014; Green, Draper, & Helton, 2014; Green & Helton, 2011; Woodham, Billinghurst, & Helton, 2016). It is likely that the true cognitive resource structure requires a blending of the unitary and multiple resource theories, incorporating both individual resource pools as well as an overall executive resource demand and certain processing bottlenecks. An acceptance of multiple resources does not mean ruling out an overarching central resource pool.

1.1.3 The Integration of Attention and Memory

The human brain is a remarkably efficient machine, yet scientists ironically have yet to figure out *how* the processor fully works. It is often hard to rank models based on objective truth because most are appropriate for certain phenomena but fail to explain all possible phenomena. In critically evaluating potential models of the human cognitive processing system, one must note that it is difficult to completely divorce the idea of *resources* (or attention) from *memory*. In many ways, memory theories share a similar debate regarding the modular way that the brain processes and utilizes information. Baddeley's working memory model provides a parallel argument to Wickens' MRT – the brain has distinct regions, processes, or capacities that handle different demands in different ways, and can potentially work with simultaneous inputs at once so long as they utilize separate stores of the cognitive device. Cowan stated that, "a sharp distinction between memory and attention is not always drawn. There is indeed a complex and intimate relationship between memory and attention," (Cowan, 1995, p. 40). Though the vast majority of memory research is outside the scope of this dissertation, some of the current stances on the division of memory must be mentioned, especially where they relate to the cognitive resource structure.

The information processing framework has been generally accepted in recent memory research. The overarching concept is that memory is made up of different parts: the sensory memory, working memory, and long-term memory. Immediate perception and processing occur in the first two systems respectively, whereas the long-term memory stores a more permanent collection of knowledge or experiences. The information processing model of memory replaced the widely known multistore model, which was a unitary, structural model comprised of a sensory register, short term memory, and long term memory (Atkinson & Shiffrin, 1968). This groundbreaking theory inspired a great deal of research, but too many shortcomings were discovered for it to remain the most accepted model. Craik and Lockhart (1972) countered with their levels of processing model. They believed that memory was a function of the depth of processing of an item (shallow/perceptual versus deep/semantic), and did not recognize a particular structural component or distinction between short and long term memory. Baddeley and Hitch (1974), on the other hand, thought the memory system was very specifically structured. Their model suggested that people have a *working* memory rather than a short term memory. Cowan (1988) suggested that working memory is not its own unique system, but part of the short *and* long term memory.

Working memory is a term that generally refers to a system with a limited storage capacity that enables people to temporarily work with certain pieces of information that can be used for comprehension, learning, and reasoning (Baddeley & Hitch, 1974). The working memory model strayed from the outdated unitary store idea towards a multimodal, limited capacity system for processing, manipulating and storing short term information, in a similar way Wickens abandoned a unitary resource perspective for the more complex MRT.

The working memory model involves independent processing systems. The central executive is the so-called 'engine' behind the operation. It drives the working memory by directing attention and allocating information into the appropriate subsystem, processes certain cognitive tasks (e.g., planning, problem solving), and draws relevant information from long term stores. On its own, however, the central executive has no storage capacity. The slave systems are utilized by the central executive to store and process specific types of information. The visuo-spatial sketchpad works with visual and spatial information, while the phonological loop deals with verbal (either spoken or written) material. The first part of the phonological loop is the phonological store, which can store speech sounds. The articulatory control process, alternatively, is used to rehearse and store the information from the phonological store.

Though the central executive is the most important component of the working memory system, it is still not fully understood. It is important in directing its slave systems, as well as managing which stimuli are attended to. This is particularly important when multiple stimuli are vying for attentional resources, as the central executive must prioritize and then actively attend to certain things while ignoring others. In and of itself, the central executive is not considered a memory store so much as control system, while the phonological loop and visuo-spatial sketchpad store specialized pieces of information. The central executive facilitates the entry of certain perceived information into these stores.

Cowan (1988) used the term central executive to refer to all types of information processing or transfer that are under voluntary control. When referring to a central executive, it does not have to fit into the strict model of Baddeley and Hitch – it is now a basic component of memory that has been accepted in addition to the general sensory/working/long term stores (Cowan, 1988). It likely involves a variety of different, yet interconnected processes. It is also assumed that the central executive has a limited capacity for processing. Cowan suggests that the amount of capacity a task requires depends on the amount of work the central executive needs to perform the necessary transfer operations (e.g. manipulating and moving information among the different stores), and suggests that the capacity is *not* domain-specific. In other words, tasks that require more effort will interfere more with one another than less effortful tasks would, but the interference could be due to conflicting memory codes rather than similar executive operations (Cowan, 1988).

Though the central executive is not necessarily limited by domain specificity, the working memory model suggests that if different tasks use the same *component* of working memory (i.e., the same slave system), they cannot be successfully done simultaneously. Conversely, if they use different components, people should be able to perform them together as well as they would separately. Dual-task research has shown that tasks using different components of the system, for example a digit span task (phonological loop) and a verbal reasoning task (central executive) could be performed simultaneously without a performance impairment (Hitch & Baddeley, 1976). When participants were required to remember a longer list of digits, they took negligible additional time to answer the verbal reasoning questions, and performance did not suffer.

It should be noted that the working memory model was updated to include the episodic buffer, which helped to better explain a variety of experimental outcomes (Baddeley, 2000, 2012). This is an additional store, intermediate to the working memory and long term memory. Though no memory model is universally accepted, the general stages of memory formation seem to exist in most. In the most basic of terms, one must first perceive stimuli, encode what was perceived, and then incorporate, consolidate, and store the information which is then made available for recall when triggered. In addition to being broken down into the temporal process of storing a newly perceived piece of information as a memory, the human memory system can also be broken down into different *types* of memories.

When memory is spoken of colloquially, it likely refers to the long term memory, or the final storage system in the temporal model. Long term memory includes explicit or declarative memory (e.g., facts and events of which people are consciously aware), as well as implicit or procedural memory (unconscious skills). Declarative and procedural memories tend to be stored in different brain regions, the former in the medial temporal lobe (e.g., hippocampus) and the latter in regions more devoted to motor control (e.g., cerebellum and motor cortex). Declarative memory is further divided into episodic memory, which are memories of events and experiences, and semantic memory, which are things such as facts and concepts. Episodic memories usually include a timeline, context, and possibly an emotional charge. Semantic memories are comprised of factual knowledge typically not tied to context or experience (Anderson, 2015).

The repeated tasks used in this dissertation – verbal recall and situation awareness (SA) - might be distinguished from one another based on these categories. The verbal recall task requires participants to memorize a list of unrelated words – semantic content. Though participants may use mnemonic devices or other memory aids such as weaving the words into a story that is easier to remember, this process inherently requires additional working memory processing. The story narrated for the SA task on the other hand is comprised of its own timeline and context. The components to be remembered are already incorporated into a larger story, making it easier to process on a deeper level. Also, participants do not rehearse the story in an attempt to remember it word for word – this would be virtually impossible. While the words of the recall task are likely to remain in working memory as they are being rehearsed, it is possible that the SA scenario is able to move into the long term memory more easily and thus the limited capacity of the working memory is less of a bottleneck when dual-tasking. Finally, the load on the central executive is likely less in the SA task - repeating the words to remember for free recall likely requires more executive control than listening to the SA story for recognition purposes only.

1.2 Interaction between Physical and Cognitive Tasks

An additional interest in this dissertation research is how physical demand affects dual-task interference. Many professions, such as military, police, search and rescue, and firefighting, along with most sports, require planning and decision making while simultaneously keeping up a high level of bodily movement and control. It is important to understand how the demanding physical activity interacts with the ability to perform other important and potentially dangerous job requirements.

Exercise scientists have done extensive work to address this question. A study run by Smit, Eling, Hopman, and Coenen (2005) showed that mental and physical effort affect vigilance differently and do not interact, but other research has suggested that the relationship is nowhere near this straightforward. Mental effort is known to decrease subjective and physiological alertness over time, and physical effort on the other hand may increase "physiological vigilance," but the way they affect cognitive processing together is ambiguous (Smit et al., 2005).

The reticular-activating hypofrontality (RAH) model of acute exercise suggests that intense physical effort diverts a limited supply of metabolic resources away from the frontal lobe that is necessary for complex cognition (explicit, rule-based cognition) but not necessarily automated reactions (implicit cognition) (Dietrich & Audiffren, 2011). Therefore, intense physical activity may detract from higher order cognitive processes but not necessarily simple reaction time or choice reaction time tasks (Dietrich & Sparling, 2004). Gutin showed that specific exercise intensities differentially affect certain types of mental tasks, and that in general shorter duration, moderate exercise was beneficial to mental tasks while longer, more strenuous exercise was detrimental (Gutin, 1973). The greater the energy demand of a physical task, the more attention necessary to control movements and the less available to devote to a cognitive task (Brisswalter, Collardeau, & René, 2002; Gutin, 1973). It has also been demonstrated that acute, submaximal exercise can improve cognitive performance but that maximal intensity exercise can hinder it (Powell, 1975). Exercise protocols of short duration and moderate intensity have tended to show beneficial effects on cognitive functioning (Tomporowski & Ellis, 1986). When exercise of even moderate, sustainable intensity lasts for over an hour however, fatiguing symptoms are shown to be detrimental to cognitive performance (Brisswalter et al., 2002). In general, most exercise studies have operated under the assumption that physiological arousal from exercise narrows attentional focus (Brisswalter et al., 1997) - just as a stressor would cause sympathetic nervous system activation, narrowing focus, preparing the body for a fight or flight response - but that too much stimulation can have detrimental effects. In other words, the effect of exercise on cognitive performance may resemble the inverted-U effect (Brisswalter et al., 2002).

An increase in cerebral blood flow is also seen with exercise (Brisswalter et al., 2002), which means that the brain is getting more oxygen and glucose - essential elements for cognitive processes. Unfortunately, these increases are not without limit. An important message to extract from the RAH model is that while the increase in arousal due to exercise can be beneficial to cognitive processes, resources are in fact still limited (Dietrich, 2006; Dietrich & Audiffren, 2011; Dietrich & Sparling, 2004) – a parallel claim to those made by cognitive resource theorists. A seemingly global increase in cerebral blood flow or processing resources, the initial response to an increased demand, cannot be maintained. According to the RAH theory, the brain eventually diverts resources from higher-order processes to the regions essential for exercise and basal functions (Dietrich & Audiffren, 2011).

A myriad of studies have examined the relationship between exercise and cognitive function (Etnier et al., 1997), due to the nearly unlimited number of ways to combine different exercise protocols with diverse cognitive tasks - not to mention the complex timing of how they are chosen to alternate or overlap. Tiny shifts in methodology can yield both statistical and practical differences in outcomes. However, a gap in the research still exists. To date, this line of research has primarily used cyclic laboratory exercises such as stationary cycling and treadmill running, rather than cognitively demanding and ecologically valid tasks. Running on a treadmill requires minimal cognitive resources, demonstrated by the ability of a de-cerebrate cat to do it (Whelan, 1996). When it comes to exercise, not all types are created equal, and exercise scientists have yet to explore the cognitive demands of more complex physical tasks with high risk physical demands. Rock climbing, for example, is very cognitively demanding (Darling & Helton, 2014; Green & Helton, 2011). A more cognitively demanding physical task may inhibit simultaneous performance on other cognitive tasks due to a central executive bottleneck. It may also require differential levels of bodily coordination, motor planning, spatial awareness, and perhaps even anxiety - tapping into not only a central resource, but perhaps interfering directly with the cognitive task on one or several of Wickens' suggested dimensions. In this dissertation, one aim of the researcher is to explore how performance on a cognitive task is affected by a simultaneous complex physical task and vice versa.

1.3 Dissertation Overview

Dual-task procedures can help determine the attentional demand of an activity by noting the degree of interference caused by a simultaneous task. Unfortunately, the MRT cannot be tested with a single dual-task pairing. Several task-pairs must exhibit differential levels of interference in order to provide evidence for the different resource pools. For example, if task A and B have a certain level of interference, task C may interfere more with task A and less with task B, while task D may interfere more with task B than A, due to different specific resource requirements. The experiments in this dissertation thus mix and match a variety of dual-task pairs to assess what happens in light of MRT predictions.

Each experimental chapter in this dissertation (2-9) describes a self-contained study. These chapters have been adapted from published or prepared-for-submission manuscripts, and therefore have their own introductions and discussions. Each chapter has been adapted for better flow and emphasis on the contribution to the bigger picture. Some of the articles were originally written as multi-experiment studies, for the sake of a greater overall impact and strength of conclusions when submitting for publication in a journal. Therefore, some sections may be abbreviated to avoid redundancies, or they may refer the reader to an earlier chapter to help complete the story.

The experiments in this dissertation were conducted to collectively explore the theme of the human cognitive resource structure as it relates to neuroergonomics in real-world operations. Each experiment employed dual-task methodology using either a free recall or situation awareness verbal memory task paired with a variety of physical and mental tasks, in both applied and laboratory settings. Though the purpose of each individual chapter should be self-evident, a comparative analysis and explanation of their collective contribution to the theme will be further explained in Chapter 10.

The first experiment, found in Chapter 2, explores the interference between a semantic discrimination task and a verbal free recall task. This experiment also explored the vigilance decrement in both the single- and dual-task in order to demonstrate the validity and utility of the new vigilance protocol. Chapter 3 explores the interference of an outdoor running task and the verbal recall task to investigate whether physical exertion in a real, outdoor field task affects one's ability to process and remember verbal information, despite a lack of overlap on Wickens' model. Chapter 4 explores whether a visual-spatial puzzle task interferes with the verbal recall task, in order to better understand the role of planning and executive processing in dual-task interference. It was chosen in particular as a seated alternative to compare to a climbing task found in previous research. Chapter 5 pairs the semantic discrimination task with a new situation awareness (SA) task used in place of the verbal recall task, to explore whether the level of interference is different when the memory demand shifts from a rote memory task to an operationally relevant memory task. Chapter 6 explores the interference between the SA task and running, and Chapter 7 explores the interference between the SA task with an indoor climbing traverse, to make further comparisons within the SA group, as well as to compare dual-task interference caused by the SA task opposed to the free recall task. Chapter 8 explores the interference between the SA task and the puzzle task, and Chapter 9 explores the interference between the SA task and a Sustained Attention to Response Task to further fill the growing matrix of dual-task comparisons.

Though in this dissertation the researcher, at times, refers to the recall or SA task as the primary task, and the other various tasks as the secondary tasks, this terminology was for ease of distinction only: participants were instructed in every experiment to do their best on both tasks. Participants were also not informed of the dual-task performance hypotheses.

The number of participants in each experiment (N) was set given realistic constraints. The number was maximized given the size of the available participant pool (e.g. a specific undergraduate class), and N was set at 12 for the physical tasks based on the counterbalance, previous research, and limited sample availability. There was an attempt to counterbalance the order of tasks across participants in all experiments, however, individuals were occasionally removed subsequently for a variety of reasons (e.g. failure to comply with instructions, technical problems). However, this seldom happened and there was no systematic relationship between the orders and the individuals removed.

Using the collection of experiments in this dissertation, the researcher aims to provide evidence for a fuller understanding of the cognitive resource structure, and a critical, systematic evaluation of the MRT. The researcher touches on what types of resources the different tasks require, and attempts to explain why certain performance breakdowns occur. Another aim is to better understand the role of physical demand in dual-tasking interference. The goal of this research is to systematically evaluate whether the MRT is an appropriate model of human cognition, or whether it requires certain modifications such as a greater emphasis on the executive resource bottleneck or general resource pool above and beyond the independent resources.

2 Interference between Semantic Discrimination and Verbal Recall

2.1 Abstract[1]

Resource theory is a common explanation for both the performance decline in vigilance tasks, known as the vigilance decrement, as well as the limited ability to perform multiple tasks simultaneously. The limited supply of cognitive resources may be utilized faster than they are replenished resulting in a performance decrement, or may need to be allocated among multiple tasks with some performance cost. Researchers have proposed both domain specific, for example spatial versus verbal processing resources, and domain general cognitive resources. One challenge in testing the domain specificity of cognitive resources in vigilance is the current lack of difficult semantic vigilance tasks which reliably produce a decrement. In the present research, it was investigated whether the vigilance decrement was found in a new abbreviated semantic discrimination vigilance task, and whether there was a performance decrement in said discrimination task when paired with a word recall task, as opposed to performed individually. As hypothesized, a vigilance decrement in the semantic discrimination task was found in both the single-task and dual-task conditions, along with reduced discrimination performance in the dual-task condition and reduced word recall in the dual-task condition compared to the respective single-task conditions. This is consistent with resource theory. The abbreviated semantic discrimination task will be a useful tool for researchers interested in determining the specificity of cognitive resources utilized in sustained attention tasks.

[1] Published paper. This chapter is based on the following paper: Epling, S. L., Russell, P. N., & Helton, W. S. (2016). A new semantic vigilance task: Vigilance decrement, workload, and sensitivity to dual-task costs. *Experimental Brain Research, 234*(1), 133-139. doi:10.1007/s00221-015-4444-0

2.2 Introduction

People are often unable to sustain their attention over extended periods of time on tasks where critical stimuli, or targets, rarely occur relative to more frequently occurring neutral stimuli (Mackworth, 1948; Szalma et al., 2004). The ability to correctly detect targets often declines with time on task, a phenomenon labelled the vigilance decrement (Helton & Warm, 2008). Despite extensive research on the vigilance decrement spanning decades, there remains extensive theoretical debate in the literature about the underlying mechanisms resulting in the decrement function (Ariga & Lleras, 2011; Head & Helton, 2014b; Head, Helton, Russell, & Neumann, 2012; Helton & Russell, 2011a, 2012; Kurzban, Duckworth, Kable, & Myers, 2013; Langner & Eickhoff, 2013; Langner, Willmes, Chatterjee, Eickhoff, & Sturm, 2010; Lim, Quevenco, & Kwok, 2013; Ross, Russell, & Helton, 2014; Thomson, Besner, & Smilek, 2015; Thomson, Smilek, & Besner, 2015). The most extensively developed theoretical model currently proposed for the vigilance decrement is cognitive resource theory (Helton & Russell, 2015; Parasuraman & Mouloua, 1987). In this theory, information processing, cognitive or attention resources are a set of renewable resources of limited supply. These resources can be temporarily depleted (consumed), although the resources can later be replenished, like other natural renewable resources. Because these resources are limited, they are also subject to trade-offs between various activities. As Herbert Simon (1969, p.31) eloquently summarized, “Scarcity is a central fact of life. Because resources – land, money, fuel, time, *attention* – are scarce in relation to our uses for them, it is a task of rationality to allocate them.” An actual signal detection decrement - a reduction in the ability to accurately separate targets from neutral stimuli or noise - is due to two possible mechanisms from a resource theory perspective: first, the rate of resource utilization and consumption outstripping the rate of replenishment and second, reallocation of the necessary resources to alternative activities.

While the underlying neural mechanisms of resource theory are being investigated at an ever increasing rate (Fernandez-Duque & Posner, 2001; Lim et al., 2010), a useful behavioral research strategy to explore resource theory is to employ dual-task methods (Caggiano & Parasuraman, 2004). In these dual-task studies, participants perform a vigilance task in conjunction with another task. Theories of working memory in particular increasingly incorporate an attention component (Cowan, 2011) and vigilance researchers have also indicated the tight interrelationship between working memory and the vigilance decrement (Parasuraman, 1979). Vigilance and working memory tasks when examined with brain imaging share overlapping neural activation in the prefrontal cortex (Helton & Russell, 2015). The type and extent of interference between tasks, according to Wickens’ Multiple Resource Theory (2008), depends on the overlap of the tasks on four possible parameters: stage of processing (perception, cognition, or response), sensory modality (visual, auditory, or other), code of processing (spatial or symbolic), and focal versus ambient vision. The more similar two or more tasks are along these parameters, the more difficult it is to effectively share attention between them because those specific resources are overtaxed.

Caggiano and Parasuraman (2004) utilized a dual-task paradigm in which participants performed a visuospatial vigilance task while also performing either a spatial or verbal working memory task. When the spatial vigilance task was performed in conjunction with the spatial working memory task there was a more pronounced vigilance decrement, in comparison to when the visuospatial vigilance task was performed in conjunction with the verbal working memory task. Extending this work in a series of studies, Helton and Russell (2011b, 2013, 2015) had participants perform visuospatial and alpha-numeric vigilance tasks with or without a concurrent memory load from another match to sample task. The vigilance task performance was impaired when simultaneously having an additional memory load. There was evidence of both domain general dual-task costs, whereby any additional memory load reduced vigilance performance, as well as some evidence of domain specific dual-task costs, e.g. more interference with a visuospatial task when having an additional visuospatial memory load.

Unfortunately the abbreviated vigilance task (Temple et al., 2000) employed by Helton and Russell, while based on a letter discrimination task, is simple enough that it could be done completely by object recognition (i.e. line detection) instead of requiring semantic or verbal processing systems. Therefore, researchers need a relatively brief verbal or semantic vigilance task that generates a decrement quickly for use in larger sample studies or studies employing brain imaging. Researchers in the past distinguished cognitive (semantic) and perceptual vigilance tasks, and noted the relative difficulty of detecting a vigilance decrement with semantic stimuli (Deaton & Parasuraman, 1993). Recent research has demonstrated a vigilance decrement for masked or noisy speech targets (Shaw et al., 2013) and this fits with prior research that making identification of semantic stimuli difficult by perceptually degrading them can facilitate vigilance decrement of semantic targets (Parasuraman & Mouloua, 1987).

In the present study an experiment with a new semantic discrimination vigilance task was conducted. Head and colleagues (Head, Russell, Dorahy, Neumann, & Helton, 2012) created a word vigilance task that incorporated semantic meaning; however, the current task provides a methodological improvement via an increased variety and complexity of word stimuli. In the task participants discriminated words that named living things from words naming non-living things. Word salience (contrast to the background) was reduced by presenting them on the same masking field used by Temple and colleagues (2000) in the abbreviated vigilance task. Participants performed this semantic discrimination task in both a single-task condition and a dual-task condition where they performed a word listening and later free recall task that has been employed in previous studies (Darling & Helton, 2014; Green & Helton, 2011; Head & Helton, 2014b). Participants perform the word listening and later free recall task in a single-task version. A vigilance decrement in the semantic discrimination task was expected in both the single-task and dual-task conditions. Reduced discrimination performance and reduced word recall were expected in the dual-task condition. Participants also reported subjective workload after each condition, and it was expected that the subjective workload profile of the new semantic discrimination task to be characteristic of vigilance tasks in general (high mental demand and frustration, and low physical demand).

2.3 Method

2.3.1 Participants

Fifty-three undergraduate and postgraduate psychology students (30 women) at the University of Canterbury served as participants for course credit. All participants had normal or corrected-to-normal vision, normal hearing, and were fluent English speakers based on self-report. Age of participants ranged from 20 to 36 years (*M* = 22 years, *SD* = 3.01). The study was approved by the University Human Ethics Committee, and informed consent was gained from each participant.

2.3.2 Materials

2.3.2.1 Word Recall Task

Words used for the word recall task were taken from those used by Darling and Helton (2014). These consisted of two, 20-word lists from the Paivio and colleagues (Paivio, Yuille, & Madigan, 1968) word pool. Words were balanced for frequency, concreteness, imagery, and meaningfulness, each with two syllables and five to seven letters (see Appendix A for full lists). The words were recorded by a male New Zealand speaker using a Behringer C-1 studio condenser microphone and Ableton Live recording program (Green & Helton, 2011).

2.3.2.2 Semantic Discrimination Task

Two lists, each of 48 “living” words (targets) and 192 “non-living” words (neutrals), were created for this task. Words ranged from three to seven letters and lists were balanced for average word length. An additional list of 16 target words and 64 neutral words was created for the practice task. The signal to noise ratio was 1:4 throughout the task (target word probability was .2; neutral word probability was .8). To control for the potential effect of audio stimulation or distraction present in the dual-task as opposed to the memory imperative, a list of scrambled “words” (Green & Helton, 2011) was created by cutting the words of a third recorded list into segments and rearranging those segments (using the Ableton Live program) to create a list of items that were no longer recognizable as English words. This list was played during the discrimination alone task.

2.3.2.3 Dual-Task

The second target-neutral list created for the discrimination task was used here, along with the second 20-word list for the recall task. The pairings of discrimination and recall lists were counterbalanced among participants.

2.3.2.4 Questionnaire

The NASA Task Load Index (TLX) (Hart & Staveland, 1988) was used to collect the six subscales of participants' subjective workload: mental demand, physical demand, temporal demand, performance, effort, and frustration. A paper and pencil version (see Appendix C) was used such that participants could rate the appropriate measure on a scale of 0-20. These were then multiplied by five and averaged across the six subscales to get an average workload measure out of 100.

2.3.3 Procedure

Participants were tested at individual cubicle workstations in a larger 35-workstation computer laboratory at the University of Canterbury. Participants were run in groups, ranging in size from 9 to 25 people. Participants were unrestrained and seated approximately 50cm from eye-level screens (377 x 303 mm, 60 Hz refresh rate). Participants wore headphones and were instructed to adjust the computer loudness to a comfortable level before beginning. If they found the volume to be too low upon commencement of the experiment, the program was immediately aborted and restarted after volume was adjusted again. Stimulus presentations (both audio and visual) and recordings of reaction times and accuracy were executed by PC computers using E-Prime Professional 2.0 (Schneider, Eschman, & Zuccolotto, 2002).

Participants read instructions on how to complete the experiment and were given the opportunity to ask questions. They were then given a 100 second practice session on the semantic discrimination task where they heard performance feedback on hits and misses. If they had no further questions after the practice, they proceeded to the experiment. Participants were assigned to one of six groups which counterbalanced the order of the three tasks (recall alone, discrimination alone, dual-task) in a within-subjects design. Audio and visual word lists were also counterbalanced.

For the word recall task, participants heard one word every 15 seconds, a total of 20 words in five minutes. Computer screens remained blank and participants were instructed to listen and remember as many words as possible. At the end of five minutes, participants were given one minute to write down all the words they remembered.

For the semantic discrimination task, participants monitored the computer screen and responded to living words with the spacebar, and withheld responses to non-living words. Neutral and target stimuli were randomly sampled without replacement from the appropriate list such that there were 16 target and

64 neutral words presented in each of three 100 second blocks in a five minute task. Targets and neutral stimuli were presented in E-prime silver transparent Arial size 20 font, centered on a mask consisting of a grid of black outlined circles, as seen in Figure 2-1. The mask appeared 133mm tall by 178mm wide, and the rest of the screen remained white. The mask was visible throughout the entire trial and was overlayed for 250ms every 1250ms by a target or neutral word. During this task, participants heard 20 scrambled words with no memory imperative as an auditory control for the words in the recall task.

For the dual-task, both of the above tasks were run simultaneously. Participants heard 20 new words to remember, while also responding to the discrimination task. At the end of five minutes, participants were given one minute to write down all the words they remembered from the audio task. At the end of each of the three tasks, participants filled out the NASA-TLX before proceeding to the next section.

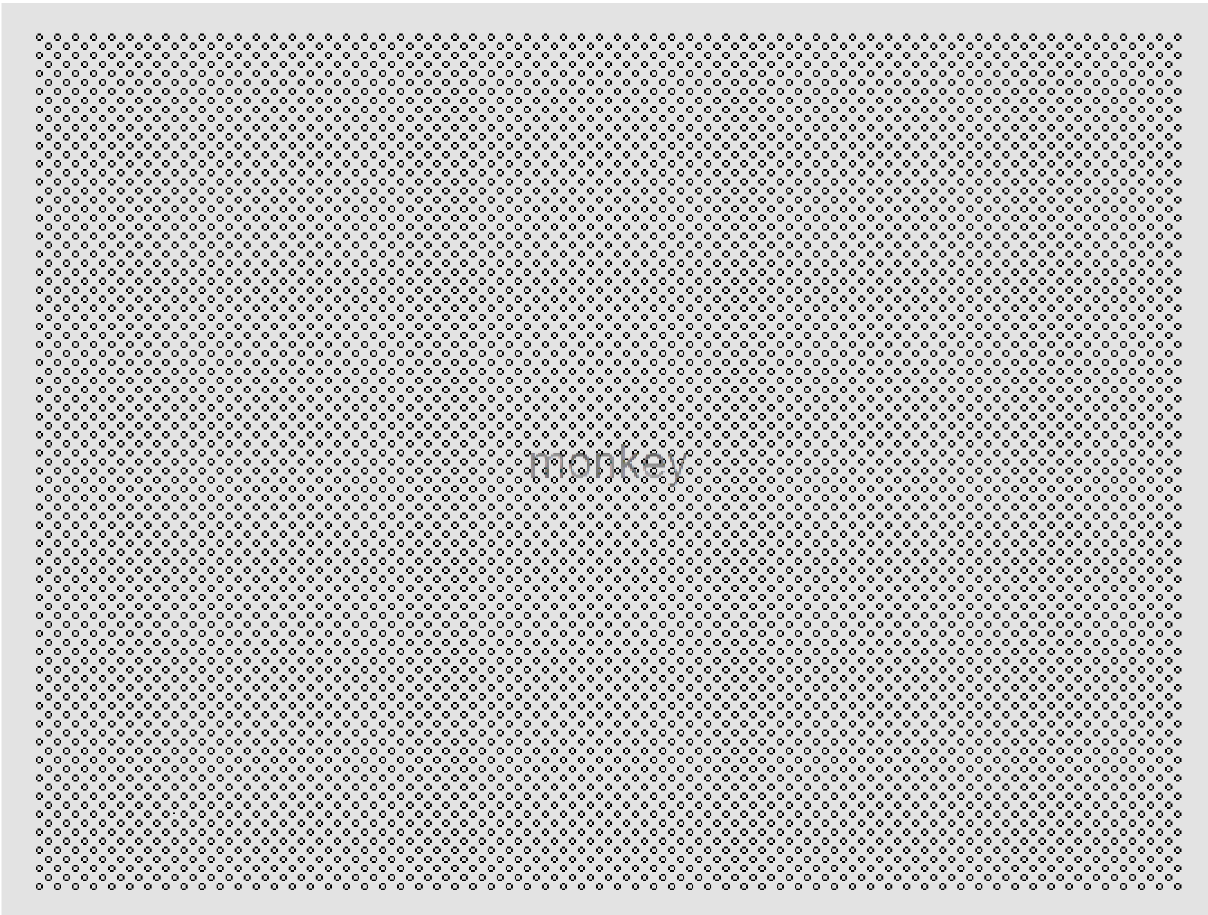

Figure 2-1. The semantic discrimination task display with a target word.

2.4 Results

2.4.1 Word Recall

The number of words recalled in the single-task (word recall task alone) condition was higher (*M* = 13.09; *SD* = 3.91) than in the dual-task (word recall task and discrimination task) condition (*M* = 8.04, *SD* = 8.04), *t*(52) = 9.25, *p* < .001, $M_{difference}$ = 5.06 (95% CI [3.96, 6.15]). From the number of words recalled the percentage of information lost was calculated using the formula [(1-#words dual/# words single)*100], *M* = 35.32, *SD* = 29.06. Percentage of information lost was compared with previous studies also using the word recall task. Results are displayed in Figure 2-2.

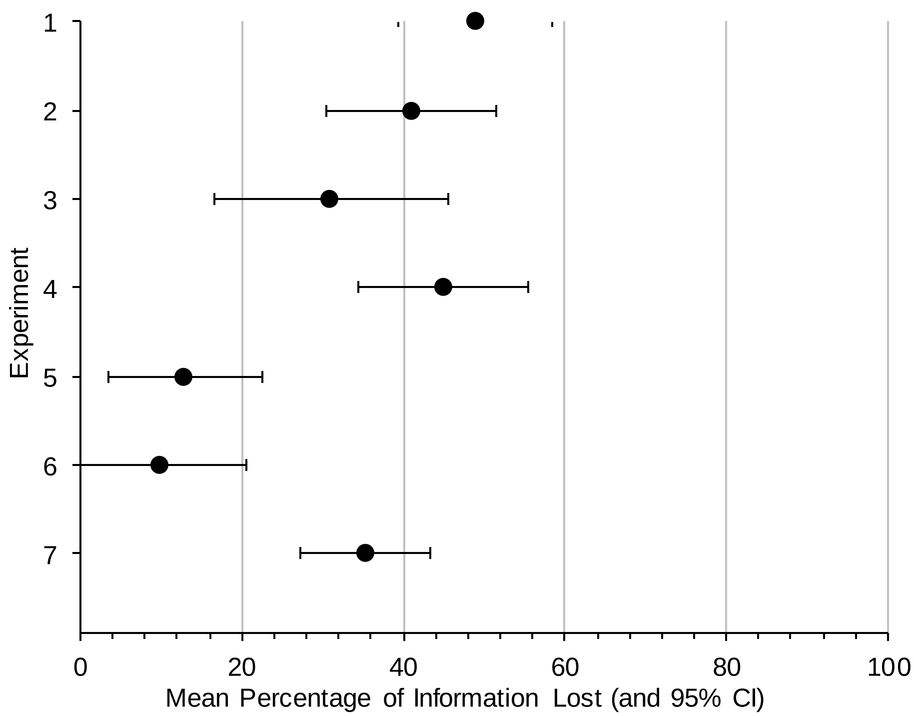

*Figure 2-2. The mean percentage of information lost [(1-# words recalled dual-task/# words recalled single task) * 100] and 95% confidence intervals for seven experiments using the word recall task for the present study (experiment 7) and previous studies examining physical climbing (experiments 1-4; Darling & Helton, 2014; Green et al., 2014; Green & Helton, 2011; Woodham, 2015) and seated manual control tasks (experiments 5 and 6; Head & Helton, 2014b; Ward & Helton, unpublished).*

2.4.2 Semantic Discrimination

For each participant the proportion of correct detections and the proportion of false alarms were calculated for each of the three 100s blocks for each task (single-task and dual-task). The signal detection theory metrics of d' (sensitivity) and c (bias) were then calculated from these proportions using the log linear correction (Hautus 1995). Both the raw proportions and the signal detection theory metrics were analyzed using four 2 (single-task versus dual-task) by 3 (block of vigil) repeated measures analyses of variance. The primary focus for the analyses regarding block and block by task interactions was with changes over blocks or trend analyses. For these tests, orthogonal polynomial contrasts were used as they are the most powerful tests of the specific hypotheses regarding change over blocks and because they are 1-df tests, violation of the sphericity assumption is not a concern.

For correct detections participants made significantly more hits in the single-task (M = .675) than the dual-task (M = .581), $F(1,52) = 39.72$, $p < .001$, $\eta_p^2 = .433$. There was a statistically significant linear trend for block, $F(1,52) = 14.64$, $p < .001$, $\eta_p^2 = .220$, but the quadratic trend was not significant, $F(1,52) = 2.44$, $p = .125$. The linear trend for the two tasks is displayed in Figure 2-3. In addition, neither the linear trend for a block by task interaction, $F(1, 52) = 2.62$, $p = .111$, $\eta_p^2 = .048$, nor the quadratic trend for a block by task interaction, $F(1,52) = .01$, $p = .922$, $\eta_p^2 = .000$, was statistically significant.

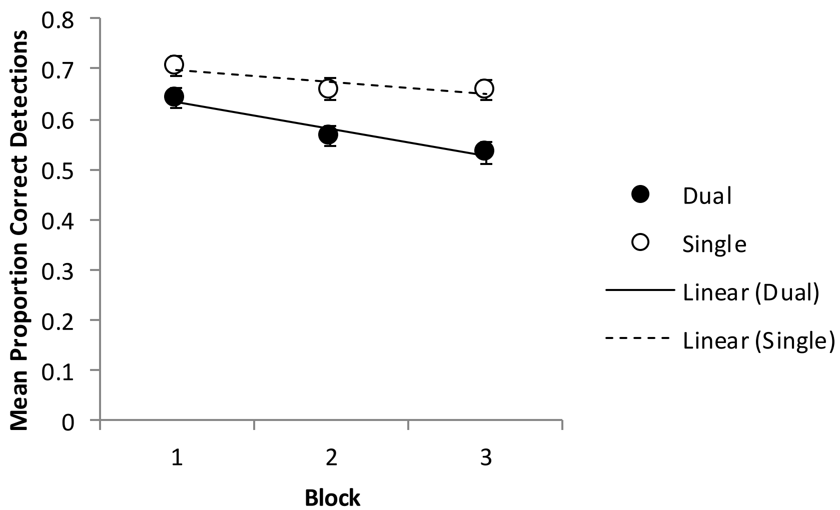

Figure 2-3. Single versus dual-task mean correct detections for block. Error bars are standard errors of the mean.

A significant difference in false alarms was not found between the dual-task (M = .034) and the single-task (M = .029), $F(1,52) = 1.73$, $p = .193$, $\eta_p^2 = .032$, though there was a statistically significant linear trend for block, $F(1,52) = 7.64$, $p = .008$, $\eta_p^2 = .128$. The quadratic trend was not significant, $F(1,52) = 2.48$, $p = .122$, $\eta_p^2 = .045$. The linear trend for the two tasks is displayed in Figure 2-4. Neither the linear trend for a block by task interaction, $F(1,52) = .057$, $p = .813$, $\eta_p^2 = .001$, nor the quadratic trend for a block by task interaction, $F(1,52) = 2.29$, $p = .136$, $\eta_p^2 = .042$, was statistically significant.

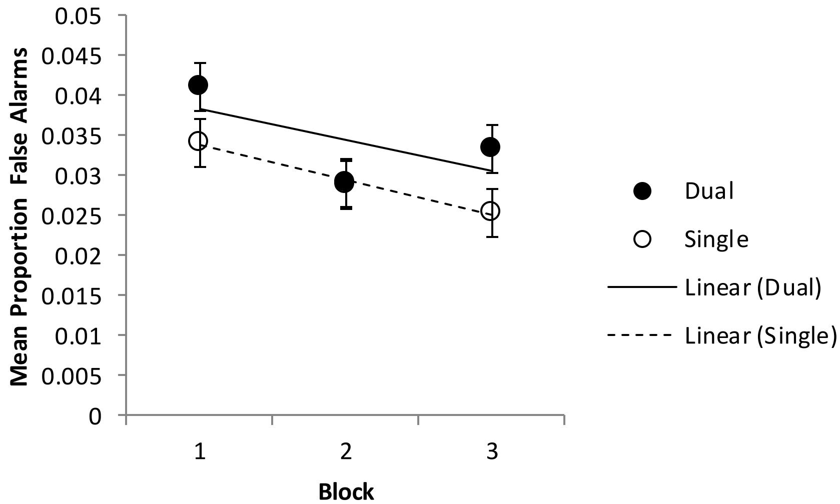

Figure 2-4. Single versus dual-task mean false alarms for blocks. Error bars are standard errors of the mean.

For d', participants had significantly higher sensitivity to the target in the single-task (M = 2.385) than the dual-task (M = 2.058), $F(1,52) = 25.99$, $p < .001$, $\eta_p^2 = .333$. There was a statistically significant linear trend for block, $F(1,52) = 4.05$, $p =.049$, $\eta_p^2 = .072$, but the quadratic trend was not significant, $F(1,52) = .02$, $p = .889$, $\eta_p^2 = 0$. The linear trend for the two tasks is displayed in Figure 2-5. In addition, neither the linear trend for a block by task interaction, $F(1, 52) = .98$, $p = .326$, $\eta_p^2 = .019$, nor the quadratic trend for a block by task interaction, $F(1,52) = 1.97$, $p =.167$, $\eta_p^2 = .036$, was statistically significant.

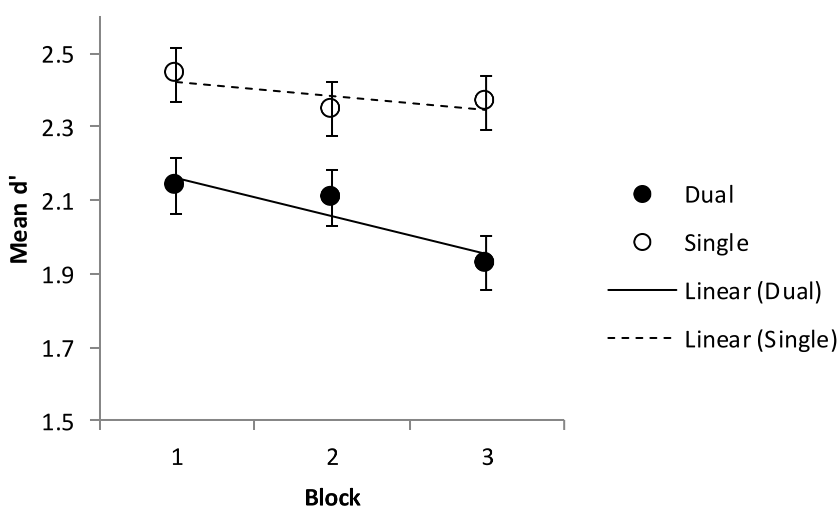

Figure 2-5. Single versus dual-task d' for blocks. Error bars are standard errors of the mean.

For c, participants were significantly more conservative in responding during the dual-task (M = .803) than the single-task (M = .704), $F(1,52) = 13.61$, $p = .001$, $\eta_p^2 = .207$. There was a statistically significant linear trend for block, $F(1,52) = 21.72$, $p < .001$, $\eta_p^2 = .295$, as well as a statistically significant quadratic trend for block, $F(1,52) = 6.69$, $p = .013$, $\eta_p^2 = .114$. The linear trend for the two tasks is displayed in Figure 2-6. In addition, neither the linear trend for a block by task interaction, $F(1, 52) = 1.55$, $p = .221$, $\eta_p^2 = .029$, nor the quadratic trend for a block by task interaction, $F(1,52) = 1.38$, $p =.245$, $\eta_p^2 = .026$, was statistically significant.

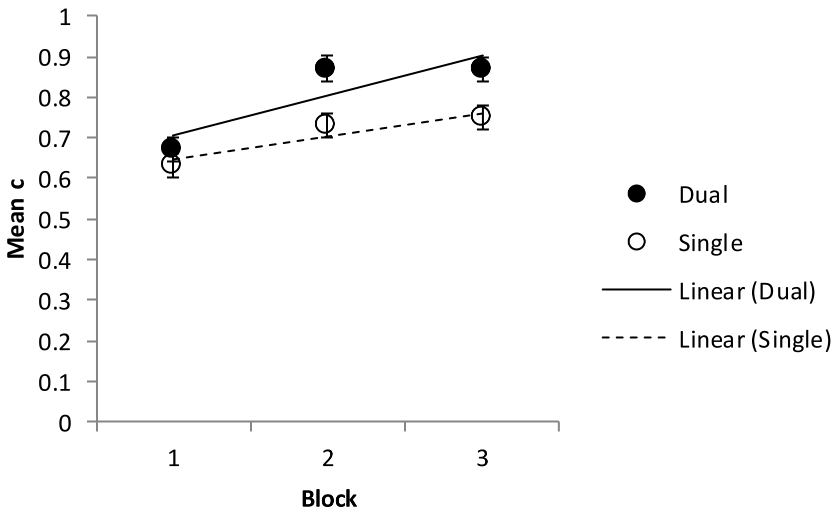

Figure 2-6. Single versus dual-task c for blocks. Error bars are standard errors of the mean.

For mean reaction time, participants were significantly faster in responding during the single-task (M = 713.53ms) than the dual-task (M = 743.76ms), $F(1,52) = 22.90$, $p < .001$, $\eta_p^2 = .306$. There was a statistically significant linear trend for block, $F(1,52) = 16.53$, $p < .001$, $\eta_p^2 = .241$, but not a statistically significant quadratic trend for block, $F(1,52) = 1.04$, $p = .312$, $\eta_p^2 = .020$. In addition, the linear trend for a block by task interaction was non-significant, $F(1, 52) = 3.00$, $p = .089$, $\eta_p^2 = .055$, but the quadratic trend for a block by task interaction was statistically significant, $F(1,52) = 8.15$, $p =.006$, $\eta_p^2 = .135$. The quadratic trend for the two tasks is displayed in Figure 2-7.

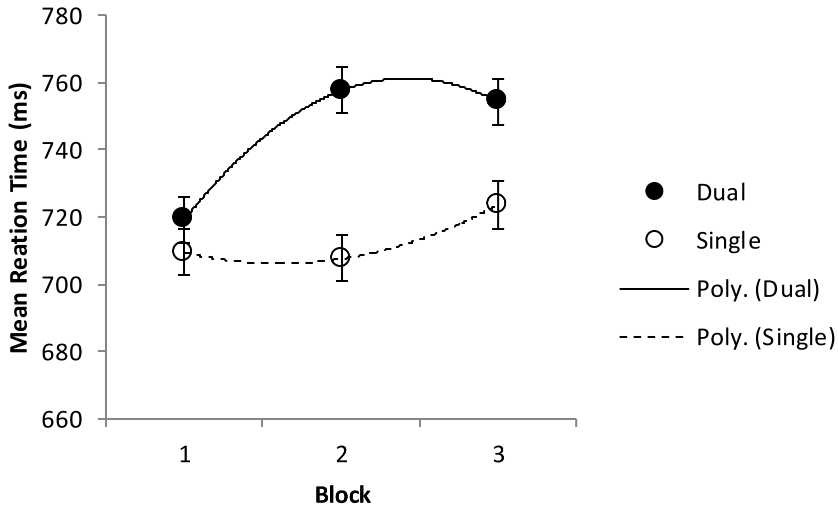

Figure 2-7. Single versus dual-task mean reaction time for blocks. Error bars are standard errors of the mean.

2.4.3 Subjective Workload

For subjective workload, the single discrimination task seems to display the typical vigilance workload profile, being high in both mental demand (*M* = 70.75, *SD* = 19.57) and frustration (*M* = 60.19, *SD* = 24.55). This is displayed in Figure 2-8. The single word recall task had the lowest average workload (*M* = 42.47, *SD* = 13.50), followed by the single discrimination task (*M* = 60.11, *SD* = 16.31), while the dual task had the highest rated workload (*M* = 66.51, *SD* = 11.34). The same trend was seen in the mental workload subscale, with single word recall being the least demanding (*M* = 62.74, *SD* = 20.13), single discrimination having an intermediate level of mental demand (*M* = 70.75, *SD* = 19.57), and the dual task being the most mentally demanding (*M* = 86.13, *SD* = 12.96).

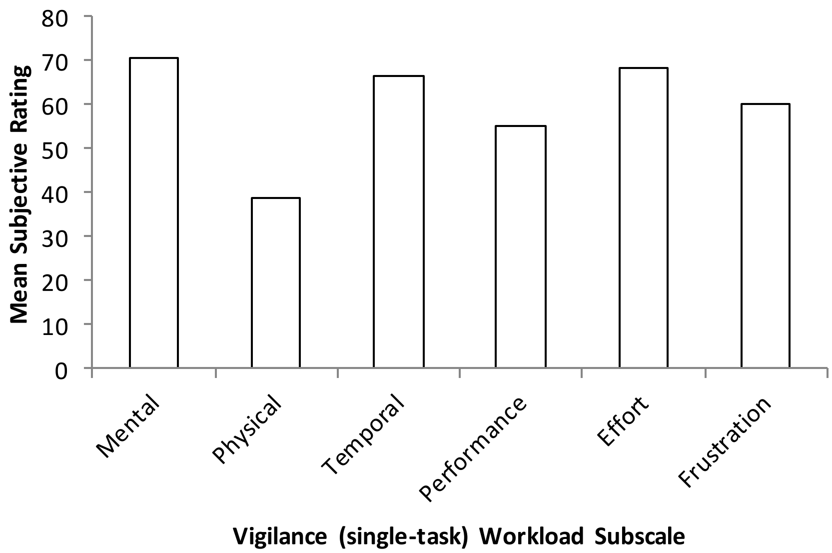

Figure 2-8. Average subjective workload profile for single discrimination task.

2.5 Discussion

In line with expectations, the semantic discrimination task elicited a vigilance decrement. For both the single- and dual-task versions, the performance metrics demonstrated reliable changes with time on task. In regards to accuracy, there was little evidence of greater performance decrement with time on task in the dual- relative to the single-task condition (i.e. no significant interactions). However, in regards to reaction time, there does appear to be some impact of the dual-task load on response slowing with time on task. While there was limited evidence of increased performance decrement in the dual-task relative to the single-task condition, overall performance was clearly degraded by the dual-task condition. Performance on both tasks (word recall and discrimination) was worse when performed together compared to alone. This is in line with a resource theory perspective of human cognition (Wickens, 2008).

The semantic discrimination task also elicited the workload profile common to vigilance tasks. Participants reported high mental demand and high frustration, but low physical demand. Future studies may also want to incorporate both subjective stress measures and objective physiological measures in studies using the semantic discrimination task.

The word recall results are also interesting when put into context with results collected from prior studies using the same word recall task (Figure 2-2). Compared to seated manual tasks (experiments 5 & 6 in Figure 2-2), word recall is substantially disrupted by performing the semantic discrimination task. This is consistent with expectations based on the MRT (Wickens, 2008), as the discrimination task required verbal resources (participants had to read and classify a continuous stream of words) which may detract from the domain-specific resources available for the word recall task (also verbal) and vice versa. The seated tracking task may have detracted from a general resource pool, but was not verbal in nature and therefore should not have interfered as much. However, the dual-task cost in this study is not substantially different from that found in prior studies where the word recall task was combined with free climbing (studies 1-4). It is not intuitive that free climbing would require a great deal of verbal resources, and this cannot be explained completely by current models. Perhaps climbing is more generally demanding, causing a central resource bottleneck, or climbers may use an internal monologue to plan their traverse the wall. Are other physical tasks as detrimental to free recall? It would be useful in the future to compare the relative costs of different tasks as this may provide insight into the underlying structure of cognitive resources.

In summary, the current semantic discrimination task demonstrated a performance decrement in a short period of time, and therefore adds to the tasks available to vigilance researchers. This will enable researchers to further explore the effects of tasks that overlap in underlying cognitive resources. Are resources used in vigilance tasks, for example, best characterized as unitary or multiple (Helton & Russell, 2015)? Researchers are encouraged to examine this issue in greater detail.

3 Interference between Outdoor Running and Verbal Recall

3.1 Abstract[2]

Resource theory is a proposed explanation for people's limited ability to perform multiple tasks simultaneously. Reallocation of a restricted supply of cognitive resources to two or more tasks may be detrimental to performance on one or both tasks. Many professionals in high-risk fields, such as those engaged in firefighting, military, and search and rescue missions, face simultaneous mental and physical demands, yet little is known about the resources required to move over the natural terrain these operators may encounter. In the present research, it was investigated whether interference would be found between outdoor running and a word recall task. As hypothesized, a reduction in word recall was observed in the dual-task compared to a recall-alone task; however, the distance run was not significantly different between the dual-task and the run-alone task. Subjective reports of workload, task focus, and being 'spent' (measures calculated from responses on a questionnaire) were greatest in the dual-task. These results support the resource theory, and have important theoretical and practical implications. Further research is required to better understand the type and extent of cognitive resources required by such physical tasks and the potential interference with simultaneous mental tasks.

[2] Published Paper. This chapter is based on the publication: Epling, S. L., Blakely, M. J., Russell, P. N., & Helton, W. S. (2016). Free recall and outdoor running: Cognitive and physical demand interference. *Experimental Brain Research, 234*(10), 2979-2987. doi: 10.1007/s00221-016-4700-y

3.2 Introduction

Resource theory is employed to explain various cognitive phenomena, such as decrements in performance with time-on-task and the inability to efficiently divide attention amongst multiple tasks (Helton & Russell, 2015; Parasuraman & Mouloua, 1987). The theory proposes that the faculties required for attention and information processing are a set of limited, yet renewable resources. Temporary depletion of resources may occur during demanding tasks (time-on-task effects), though they can be replenished like other renewable resources. Because of the fixed supply, these resources are subject to trade-offs between various activities (multi-tasking costs).

Dual-task methodology is useful for exploring the cognitive resource theory (Caggiano & Parasuraman, 2004). Performing two tasks at once allows for an assessment of which components of certain tasks cause interference, especially when the same task is paired with various secondary tasks, allowing for comparison across domains. Most research using the dual-task paradigm find performance detriment in the dual- compared to single-task conditions, regardless of the type of tasks used (Blakely, Wilson, Russell, & Helton, 2016; Bourke, 1996; Darling & Helton, 2014; Epling, Russell, & Helton, 2016; Green & Helton, 2011; Head, Russell, et al., 2012), but it has been proposed that the more similar the demands of given tasks, the greater the detriment. Wickens' Multiple Resource Theory (MRT; 2002, 2008) proposes that the extent of interference depends on the overlap of the tasks on four possible parameters: stage of processing (perception, cognition, or response), sensory modality (visual, auditory, or other), code of processing (spatial or symbolic), and for visual tasks, focal versus ambient vision. From this MRT perspective it is harder to share attention among tasks that are similar along these parameters because those specific resources are overtaxed (Helton & Russell, 2011a, 2013, 2015). However, there has been evidence that working memory tasks may require a general attention component as well, diverting resources from any secondary task regardless of overlap on Wickens' (2008) proposed cognitive matrix (Chen & Cowan, 2009; Cowan, 1995).

Though dual-task interference between certain cognitive tasks is becoming more defined, the cognitive demands of most real-world, physically demanding tasks are less understood. This makes it difficult to anticipate potential interference of these physical demands with an additional cognitive imperative, regardless of how well the latter has been demarcated in terms of required resources. There has been ample evidence that concurrent exercise, within specific intensity and duration parameters, enhances performance on implicit, automated, or simple decision making or reaction time tasks (Dietrich & Audiffren, 2011; Etnier et al., 1997), while the effect on more executive resource demanding tasks has been disputed (Labelle et al., 2013). However, even the seemingly clear beneficial effects of physical activity on simple cognitive tasks may be challenged when considering the lack of realism typically present in the cyclical, laboratory-based physical tasks that have been used in the exercise or physical task literature. Activities such as running on a treadmill and stationary cycling require very little, if any, executive processing or decision making (Whelan, 1996), which means these studies may not be applicable to real-world physical tasks. Though physical activity often has beneficial effects on thinking, it may not have such beneficial effects when the physical tasks used are more realistic. Treadmill running and stationary cycling may require fitness and physical effort, but they do not require planning or navigation, care in foot placement to avoid potential obstacles, and certainly have fewer environmental distractors than natural physical tasks.

In the present study a well-established free recall task (Darling & Helton, 2014; Epling, Russell, et al., 2016; Green & Helton, 2011) was paired with an outdoor track running task. Previous studies (Darling & Helton, 2014; Epling, Russell, et al., 2016; Green & Helton, 2011) compared recall of words presented while climbing a wall and words presented while performing a concurrent verbal task. Recall was impaired by wall climbing at least as much as a concurrent verbal task (Epling, Russell, et al., 2016), and both of these tasks resulted in worse recall than concurrent simpler seated tasks, such as manual tracking and a response inhibition task. The relative word recall loss compared to seated single-task control for these studies is displayed in Figure 3-1. A number of possibilities could be proposed to explain these findings. Dietrich and Audiffren (2011) have proposed that due to resource limitations, exercise may lead to disengagement of executive processing and other higher order processes of the prefrontal cortex in order to divert resources to where they are more urgently needed. In addition, people may have to mentally push themselves to perform physical activities, and this too may require executive resources. Another possibility is climbing itself, because it is a complex physical activity, may require the need to carefully plan movements and this motor planning may utilize executive, and perhaps, verbally mediated cognitive resources (Helton, Green, & de Joux, 2013).

In the present study flat track running was employed in place of wall climbing in conjunction with a verbal recall task to further explore the effects of physical demand and effort on verbal memory. If running reduces recall to the extent that climbing has done in previous studies, then perhaps it is something about the physical exertion (pushing oneself to do a physically demanding task) as opposed to mental planning that interferes with verbal recall. However, an alternative possibility is that something specific to different physical tasks, such as movement complexity, causes different types of interference. The tasks may also have a differential level of global (executive) demand, or require different amounts of internal dialogue (verbal demand). The methodological parallel to several prior studies using the word recall task allows for direct comparison among different cognitive and physical domains.

In this study, participants were asked to run as far as they could in five minutes. Participants ran in both a single-task condition and in a dual-task condition where they performed the free recall task described above. Participants also performed the free recall task in a seated, single-task scenario. A reduced distance run in the dual-task compared to single-task condition was expected, based on similar running and climbing dual-task research (Blakely, Wilson, et al., 2016; Green et al., 2014). Reduced word recall in the dual-task condition was also expected based on the severe reduction found in the climbing studies. In addition to performance on both tasks participants reported subjective workload and stress, using a subjective stress state questionnaire (Blakely et al., 2016). Based on the research of Blakely and colleagues (2016), the spent component, representing the degree of burn-out or exhaustion, and the task focus component, representing the participant's perception of their focus on each task, were of particular interest. The spent component, task focus component, and overall workload of the dual-task condition were expected to be greater than both single-task conditions. The run-alone condition was also expected to have the lowest task focus as a verbal cognitive task should reduce the capacity for task unrelated thoughts, and the two conditions involving a run were expected to have a greater spent component than the cognitive task alone.

3.3 Method

3.3.1 Participants

Twelve athletes (6 women) recruited in the general Christchurch region participated in this research. Participants were required to be physically fit (exercising a minimum of three days a week), healthy, fluent English speakers, and to have normal vision and hearing. Age of participants ranged from 18 to 45 years (M = 28 years, SD = 10.1). The study was approved by the University of Canterbury Human Ethics Committee, and informed consent was gained from each participant. All participants received a \$10 voucher to a local shopping mall as compensation for their time. Participant demographics and fitness related statistics are presented in Table 3-1.

Table 3-1. Participant demographics and fitness information

Participant	Gender	Age	Weight(kg)	Height(m)	BMI	PA-R	VO_2max^1	VO_2max^2
1	Female	24	61.4	1.74	20.3	6	42.8	43.5
2	Male	25	79.2	1.86	22.9	5	47.0	50.2
3	Female	25	70.7	1.65	25.9	5	42.2	36.9
4	Female	25	77.4	1.69	27.1	7	45.8	39.8
5	Male	25	71.3	1.75	23.2	7	52.8	53.8
6	Male	38	83.2	1.85	24.2	7	61.1	48.1
7	Female	45	64.1	1.72	21.8	7	46.0	36.2
8	Male	30	72.1	1.72	24.5	6	54.4	49.0
9	Male	30	80.1	1.78	25.3	5	52.1	46.4
10	Female	18	47.2	1.55	19.7	5	42.8	44.3
11	Male	27	62.0	1.71	21.2	7	51.7	54.5
12	Female	22	82.0	1.69	28.7	7	39.8	39.8

Notes. BMI is given by weight (in kilograms) divided by squared height (in meters). PA-R comes from the physical activity questionnaire used with the Jackson Non-Exercise Test. VO_2max^1 was calculated from the 1-mile jog test, VO_2max^2 was calculated from the Jackson Non-Exercise Test, see Appendix B.

3.3.2 Materials

Participants were asked to come dressed in comfortable running gear, and were supplied with a helmet (Specialized adult cycling helmet) to wear for safety. Over-the-ear headphones (Kama Triton) were attached to the helmet for the listening apparatus. Participants were required to wear a heart rate monitor (Polar RC3 GPS), and carry an IPod (model A1238) in hand during the task. A digital scale was used to obtain participants' weight (Tanita BC-532 Inner Scan Body Composition Monitor), a measuring tape was used to obtain height, golf markers and a surveyor's wheel were used to measure the distance run, and a stopwatch was used to record mile time and determine when participants' five-minute runs were complete.

3.3.2.1 Word Recall Task

See Chapter 2 for details.

3.3.2.2 Running Task

This experiment was conducted outdoors on a flat 400m oval grass track at a local public high school. Participants were run one at a time, in dry weather when the track was clearly mowed and free of obstacles. The same starting line was used for each participant, and an extra 9.3 meters was marked for the fourth lap of the one-mile run.

3.3.2.3 Dual-Task

The running and word recall tasks were performed concurrently. The particular word list participants received in the single- versus dual-task condition was counterbalanced.

3.3.2.4 Questionnaire

The subjective stress state questionnaire (Blakely, Wilson, et al., 2016), a modified workload scale derived from the NASA-TLX workload scale (Hart & Staveland, 1988) and the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 2002), was used after each task in this study. The questionnaire includes a subset of the traditional TLX subscales (mental demand, physical demand, temporal demand, and effort); in addition to the subscales of physical fatigue, mental fatigue, tense, emotional demand, performance monitoring demand, unhappiness, motivation, task interest, self-related thoughts, concentration, confidence, task related thoughts, and task unrelated thoughts (see Appendix D for the questionnaire given to participants, which includes instructions for participants and a definition for each subscale). Participants filled out the questionnaire after completing each task (word recall alone, running alone, dual-task). The ratings ranged from 0 (very low) to 100 (very high) and participants circled their ratings on the given 5 point intervals.

3.3.3 Procedure

Participants met the researcher on a footpath near the track where they were given an information packet outlining the purpose and basic instructions for the task, an informed consent document to sign, biographical details to report, and an exercise rating questionnaire. Participants were given the opportunity to ask questions. Once consent was given, participants were asked to remove their shoes and any heavy outer garments to take height and weight measurements. Once measurements were documented and shoes were put back on, the participant and researcher proceeded to bleachers next to the track.

Participants were given a chest strap heart rate monitor and instructed how to put it on themselves, along with the watch which displayed heart rate in real time. Heart rate was recorded to ensure that any potential difference in distance run was not due to a corresponding difference in physical effort. Participants were asked to take a seat on the bleachers while they were given more instructions, which allowed heart rate to return to rest. Participants were informed that they would begin with a one-mile warm-up jog, which would also play a role in estimating their VO_2 max. The VO_2max test (see Appendix B for the two models used to estimate VO_2 max) was included to give an indication of the participant's physical fitness. They were told to go at an easy, constant pace, with men completing the mile no faster than eight minutes, and women no faster than nine minutes. They were told that they would be updated of their time after each 400m lap and told whether they needed to slow down to meet requirements. Participants' resting heart rate was recorded, and if they had no questions, they were asked to proceed to the starting line on the track. Participants were instructed to begin running whenever they were ready, and the stopwatch was started as they took their first step from the line. When participants crossed the one mile mark, their time was recorded and heart rate was recorded within five seconds.

Participants were asked to take a seat on the bleachers and were allowed to drink water. They were told that they would next be doing three different tasks: a five minute seated word recall task, a five minute run, and a five minute run with recall task (dual-task condition). Participants would be allowed water and as much rest time as they needed between each task to avoid fatigue, and would be required to wear the helmet/listening apparatus for each condition. This was a within-subjects design, and participants were randomly assigned in equal numbers to the six possible permutations of the three tasks.

For the running task, participants were instructed to run as far as they could around the track in the given time. They were also told that the experimenter would begin running near them towards the end of the five minutes in order to gain an accurate distance measurement at the precise five minute point, but not to change their effort or stop running until told. Participants were not updated of their time during the five minute runs. This was the method utilized by Blakely and colleagues (2016). The stopwatch was begun when participants left the designated mark, and the experimenter used a golf marker to show the distance the participant had reached at precisely five minutes. The researcher was positioned near the participant just before the five minutes was up and began running with the participant in order to see where the foot was placed precisely as the stopwatch reached the five minute mark. The researcher told the participant to stop running and immediately put down the marker before recording the participant's heart rate. Distance was measured with the surveyor's wheel after the participant had finished the entire experiment. During this specific task, participants heard 20 scrambled words with no memory imperative. This was done as a control for the words listened to in the dual-task. The researcher had the correct audio file queued on the IPod, and participants were instructed to press play as soon as they began running. The loudness was set at three quarters of max intensity upon participants' arrival, but they were allowed to adjust the volume as they saw fit.

For the word recall task, participants were instructed to sit on the bleachers and to listen and remember as many words as possible. The researcher had the correct audio file queued on the IPod, and participants were told to press play when ready. One word was played every fifteen seconds, such that participants were presented with 20 words in five minutes. At the end of five minutes, participants were given ninety seconds to write down all the words they remembered.

For the dual-task, both of the above tasks were performed simultaneously. Participants heard 20 new words to remember, while also running as far as they could around the track in the given time. At the end of five minutes, participants were handed a clipboard and given time to write down all the words they remembered from the audio task. After ninety seconds, if participants were no longer readily recalling more words, they were told that it was time to move to the next task.

At the end of each of the three tasks, heart rate was recorded within five seconds and participants also filled out the modified workload scale and were given adequate rest. Participants self-reported when they felt ready to proceed to the next task, and the researcher checked that heart rate had fallen to approximately 100 beats per minute (bpm) or less (a cut-off level for tachycardia) before proceeding to the next task.

3.4 Results

3.4.1 Word Recall

The number of words recalled in the single-task (word recall task alone) condition was higher (M = 11.58; SD = 3.09) than in the dual-task (word recall task while running) condition (M = 9.75, SD = 4.09), $t(11) = 2.41$, $p = .034$, $M_{\text{difference}} = 1.83$ (95% CI [0.17, 3.50]). From the number of words recalled the percentage of information lost was calculated using the formula [(1-#words dual/# words single)*100], M = 16.74, SD = 21.89. This was compared to previous studies using this word recall task in the dual-task paradigm paired with tasks other than running, and these comparisons are displayed in Figure 3-1.

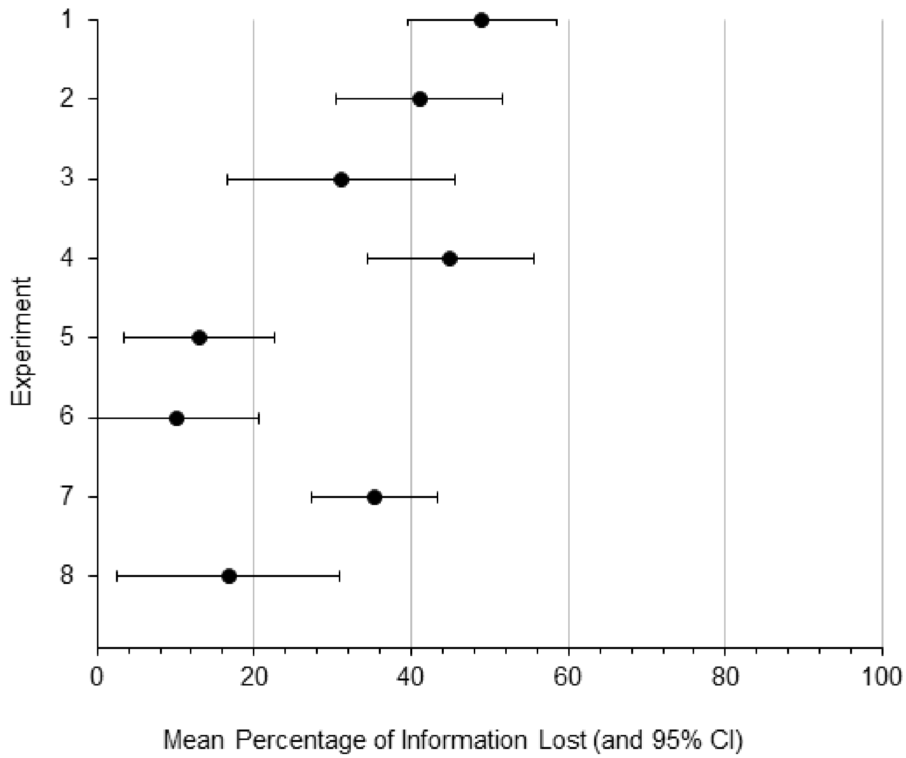

Figure 3-1. Mean percentage of information lost [(1 - # words recalled dual-task/# words recalled single-task) x 100] and 95% CI for eight experiments using the word recall task for the present study (experiment 8) and previous studies examining physical climbing (experiments 1-4; Darling & Helton, 2014; Green et al., 2014; Green & Helton, 2011; Woodham, 2015), seated manual control tasks (experiments 5 and 6; Head & Helton, 2014b; Ward & Helton, unpublished), and semantic discrimination tasks (experiment 7; Epling, Russell, et al., 2016).

3.4.2 Running

Participants ran farther on average in the single-task (running only) condition (M = 1059.2 m, SD = 199.9) than the dual-task (running and recall) condition (M = 1038.7 m, SD = 203.9), shown in Figure 3-2, though the difference was not statistically significant, $t(11) = 1.27$, $p = .232$, $M_{\text{difference}}$ = 20.5 m (95% CI [-15.2, 56.3]). There was no significant difference in heart rate immediately following the single-task (M = 183.3 bpm, SD = 6.81) compared to the dual-task (M = 182.5 bpm, SD = 8.74), $t(11) = .56$, $p = .585$, $M_{\text{difference}}$ = .8 bpm (95% CI [-3.7, 2.2]).

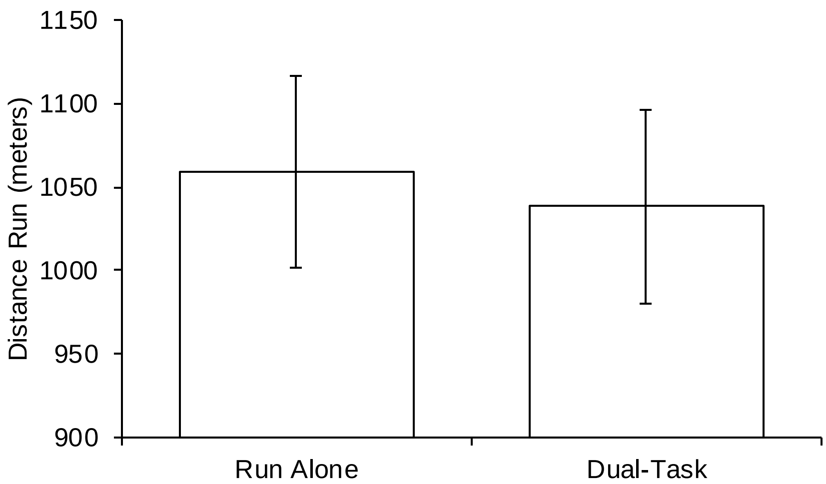

Figure 3-2. Mean distance run in the single- versus dual-task conditions, with error bars representing standard error of the mean.

3.4.3 Subjective Stress State

The average rating on each factor of the self-report scale is shown in Table 3-2. The workload component is the mean of mental demand, physical demand, temporal demand, emotional demand, performance monitoring demand, and effort. The spent component is the mean of physical fatigue, mental fatigue, tense, unhappy, and confidence (reverse scored). Task focus is the mean of motivation, self-related thoughts (reverse scored), concentration, task related thoughts, and task unrelated thoughts (reverse scored).

Table 3-2. Self-report averages

	Word Recall Alone	Dual-Task	Running Alone
Mental Demand	72.5 (6.0)	71.7 (3.9)	24.2 (4.0)
Physical Demand	5.4 (2.2)	70.4 (6.1)	72.9 (5.2)
Temporal Demand	30.0 (7.0)	45.4 (7.9)	49.2 (8.6)
Emotional Demand	12.1 (3.8)	24.2 (6.5)	22.9 (5.7)
Performance Monitoring Demand	34.2 (7.5)	52.1 (7.0)	50.0 (7.8)
Effort	64.2 (7.3)	71.3 (6.7)	70.8 (4.0)
Physical Fatigue	7.9 (2.8)	60.0 (6.4)	64.6 (4.8)
Mental Fatigue	38.8 (7.9)	48.3 (7.4)	23.8 (4.1)
Tense	31.3 (6.0)	31.7 (8.3)	27.1 (4.9)
Unhappy	18.3 (5.9)	15.8 (6.0)	10.8 (2.8)
Motivation	77.1 (4.2)	78.3 (4.5)	69.2 (4.9)
Task Interest	60.4 (4.7)	64.6 (5.2)	55.0 (6.8)
Self Related Thoughts	30.8 (6.7)	27.9 (5.2)	47.1 (7.7)
Concentration	75.0 (4.0)	82.5 (2.5)	62.1 (7.0)
Confidence	58.3 (5.4)	57.1 (4.9)	64.6 (4.1)
Task Related Thoughts	84.2 (4.2)	77.9 (4.7)	55.8 (7.6)
Task Unrelated Thoughts	20.4 (6.1)	17.9 (2.8)	41.3 (7.9)
Workload	36.4 (3.6)	55.8 (4.4)	48.3 (4.2)
Spent	27.6 (4.4)	39.8 (5.5)	32.3 (3.3)
Task-Focus	77.0 (3.5)	78.6 (2.6)	59.8 (4.3)

Notes. Each value is the mean (standard error of the mean) self-report rating across all participants for that measure, on a scale of 0-100.

Because of the interest in the difference between single- and dual-task performance, pre-planned contrasts were conducted. Tests revealed that dual-task workload (M = 55.83, SD = 15.42) was greater than run-alone workload (M = 48.33, SD = 14.38), $t(11)$ = 2.41, p = .035, and recall-alone workload (M = 36.39, SD = 12.57), $t(11)$ = 3.84, p = .003. The run-alone workload was significantly greater than the recall-alone workload $t(11)$ = 3.07, p = .011.

The spent component was greater in the dual-task (M = 39.75, SD = 18.90) than the recall-alone task (M = 27.58, SD = 15.32), $t(11)$ = 3.23, p = .008, but not significantly greater than the run-alone task (M = 32.33, SD = 11.27), $t(11)$ = 1.71, p = .115. The single-tasks also did not significantly differ from each other in the spent component, $t(11)$ = 1.08, p = .302.

Task focus was greater in the dual-task condition (M = 78.58, SD = 8.94) than the run-alone task (M = 59.75, SD = 14.74), $t(11)$ = 4.61, p = .001. Task focus was also greater in the recall-alone task (M = 77.00, SD = 12.08) than the run-alone task, $t(11)$ = 6.05, p < .001, but the two tasks involving recall did not significantly differ from each other, $t(11)$ = .624, p = .545.

3.5 Discussion

Performance on both tasks (word recall and running) was poorer when performed together compared to alone. Significantly fewer words were recalled in the dual-task than the seated cognitive task, and participants on average did not run as far in the dual-task as the run-alone task. However, the difference in distance did not reach significance. This is in line with both a resource theory perspective of human cognition, and with previous research (Darling & Helton, 2014; Green & Helton, 2011) suggesting that even without a task imperative participants will likely preserve movement task performance relative to cognitive task performance (Wickens, 2008).

3.5.1 Word Recall

The word recall results are particularly interesting when compared with results collected from prior studies using the same task (Figure 3-1). Compared to seated manual tasks requiring few cognitive and physical resources (experiments 5 & 6 in Figure 3-1), running is a little more disruptive to word recall. As predicted, this shows that running outdoors is, in fact, demanding. It should be noted that ninety seconds was more than enough time for most participants to write down recalled words in both the single- and dual-tasks, and there is no reason to believe that participants had more trouble writing down the words after the dual-task condition because they were winded from the run. The time limit for recalling words was enforced only if it seemed participants were stalling for more time to remember, not if they were in the middle of writing still freely-flowing recalled words.

Running, however, is notably less disruptive to word recall than a verbal cognitive task, and several iterations of a climbing task (experiments 7 and 1-4 respectively in Figure 3-1). This could be considered consistent with expectations based on the MRT (Wickens, 2002, 2008), as the verbal cognitive task requires more domain-specific competing resources. This could also be consistent with a unitary cognitive resource perspective because it is reasonable to argue that the climbing task requires more global resources than running, but the specific nature of the climbing and other physical task demands requires further research. Future research should examine climbing with a think aloud protocol to determine how actively climbers use verbal strategies in their movement planning (Ericsson & Simon, 1980). Basically, are climbing and other complex movement tasks more verbal than they initially appear?

3.5.2 Running

Though it was predicted that participants would not run as far in the dual-task condition, it is not completely surprising that no significant difference was found. Since participants were not told how to prioritize (only to do their best on both tasks), perhaps people naturally prefer to prioritize physical rather than cognitive demands. Movement may be prioritized as failure of the movement task could result in an injury, whereas failure of the cognitive task incurs little cost to the participant (though if the cognitive task had more real-world or life threatening consequences, this may not be the case). This assumed or unconscious prioritization could lead to task shedding of the cognitive imperative in order to maintain performance in the physical imperative, meaning that performance impairments would be more likely in the cognitive than the physical performance in the dual-task condition. This result could have also come about if participants overtly believed that running was the primary focus of the research, though this was not intended. In addition, it could be argued that though the dual-task may be "harder," some runners perform as well or better when able to keep their mind engaged on something other than the monotonous and exhausting task of putting one foot in front of the other, but this possibility requires further research. On the other hand, people did, on average, tend to run farther in the single-task condition, even though statistical significance was not reached. Though the sample size was chosen from the number of participants needed for a full counterbalance in addition to the number used in previous dual-task movement studies that found statistical significance, perhaps a larger sample size is required to find a significant difference (more statistical power may be necessary). Alternatively, measuring lap time (in addition to overall distance run) may provide additional sensitivity, as perhaps performance impairment may be more evident in the latter half of the dual-task, as the list of words being rehearsed will be longer and participants will be more physically fatigued.

3.5.3 Subjective Stress State

Workload was greatest in the dual-task condition, as expected. Since physical demand is one of the components of the workload calculation, it is also understandable that the single running task involved a significantly greater workload than the single cognitive task. Extensive work has gone into the development of self-report scales targeting workload, but in this case the comparison or combination of mental and physical workload may not be appropriate. The physical demand of the run has overshadowed potential effects to be found in the rest of the non-physical workload sub-scores. The sub-score of mental workload alone is clearly higher in the two tasks involving recall than the run-alone, but that is not to say that running does not involve any mental workload at all: the average rating was 24.2 out of 100. Perhaps a scale aimed specifically at assessing the mental workload of physical tasks would have greater precision in this domain. However, the purpose of this research in part is to assess the mental workload of the physical task indirectly through the within-subjects change in performance on the cognitive task in the single- versus dual-task conditions. By using the same cognitive task across several physical domains, the performance decrement caused by each physical task can be directly compared.

In future research it would be informative to gather more physiological data in addition to the somewhat limited performance scores on the both the physical and cognitive tasks and subjective self-reports. Development of new mobile brain imaging technology provides an interesting possibility to examine cognitive workload objectively during physical tasks (Gramann et al., 2011; Gramann, Ferris, Gwin, & Makeig, 2014; Gwin, Gramann, Makeig, & Ferris, 2010, 2011). The incorporation of mobile brain imaging may shed light on the interplay of stress levels, performance, and the actual mechanism of how a secondary task contributes to the results found. The experiment could also be repeated using trail running, treadmill running, and obstacle course running involving more complex maneuvers such as hurdles, footwork ladders, and slalom-like components in order to demonstrate just how much harder (or easier) it is to simultaneously run and think depending on the type of running being undertaken. Using different types of cognitive tasks would also contribute to a better understanding of the unitary versus multiple resource perspective, and a better understanding of what types of cognitive resources different types of running require. In addition, the duration of rest breaks was not recorded. Though the above average physical fitness of participants and counterbalanced design should prevent physical fatigue from influencing the distance run in each condition, enforcing a specified rest time may be useful to tease out the effects of cognitive fatigue.

In summary, it was found that outdoor running significantly interferes with word recall, but not to the extent of wall climbing. It is suspected that running over uneven terrain would be intermediate between climbing and flat track running (see Blakely et al., 2016). The application of lab-based physical tasks using treadmills and cycle ergometers (stationary cycling) to the demanding physical tasks required of military personnel, firefighters, and search and rescue operators should therefore be made with some caution. The need to coordinate perception and action in more ecologically realistic movement tasks may place more demands on cognition, and the more the movement task requires movement planning the more disruptive it will be to other cognitive tasks.

4 Interference between a Puzzle Task and Verbal Recall

4.1 Abstract[3]

Research continues to provide evidence that people are poor multi-taskers. Cognitive resource theory is a common explanation for the inability to efficiently perform multiple tasks at the same time. This theory proposes that one's limited supply of cognitive resources can be utilized faster than it is replenished, which results in a performance decline, particularly when these limited resources must be allocated among multiple tasks. Researchers have proposed both domain specific, for example spatial versus verbal processing resources, and domain general cognitive resources. In the present research, it was investigated whether a spatial puzzle task performed simultaneously with a verbal recall task would impair performance in either or both tasks, compared to performance on the tasks individually. As hypothesized, a reduction in word recall was found when dual-tasking, though performance on the puzzle task did not significantly differ between the single- and dual-task conditions. This is consistent, in part, with both a general resource theory and Multiple Resource Theory, but further work is required to better understand the cognitive processing system. The employment of the recall task in the dual-task paradigm with a variety of secondary tasks will help to continue mapping out the specificity (or lack thereof) of cognitive resources utilized in various mental and physical tasks.

[3] Published paper. This chapter is based on the publication: Epling, S. L., Blakely, M. B., Russell, P. N., & Helton, W. S. (2017). Interference between a fast-paced puzzle task and verbal memory demands. *Experimental Brain Research, 235*(6), 1899-1907. doi: 10.1007/s00221-017-4938-z

4.2 Introduction

People are often required to divide attention among multiple tasks. Unfortunately, people are inherently ill-equipped to multi-task. Cognitive resource theory is an extensively developed theoretical model proposed to explain the inability of people to efficiently divide attention across multiple tasks (Helton and Russell 2015; Parasuraman and Mouloua 1987). Resource theorists propose that mental, attentional, or information-processing resources are limited, but renewable. Thus, the resources can be used up faster than they can be replenished, which can lead to performance trade-offs between activities, or general performance decline across all tasks. A reduction in performance on mentally demanding tasks, according to the resource theory, is thus attributed to two mechanisms: using resources faster than they are replenished, and reallocating resources from one task demand to another (Epling, Russell, and Helton 2016).

Dual-task research methods provide a useful strategy to explore resource theory variations by having participants perform two different tasks at the same time (Caggiano and Parasuraman 2004). Usually, both tasks are also performed in single-task conditions, in order to provide a baseline for performance comparison. A general, central capacity resource theory cannot fully explain performance patterns in all dual-task pairings, however, as some tasks – regardless of objective difficulty and duration – seem to interfere with each other more than others (Epling, Blakely, Russell, & Helton, 2016; Kahneman, 1973). Wickens' Multiple Resource Theory (MRT; Wickens 2002, 2008) suggests that available resources are not necessarily a general, unitary pool of resources, but that multiple types of cognitive resources exist. Wickens proposes that the interference between tasks depends on the overlap of the tasks on a matrix that includes four specific parameters: stage of processing (perception, cognition, or response), sensory modality (visual, auditory, or other), code of processing (spatial or symbolic), and focal versus ambient vision for visual tasks. The more similar the given tasks are along any of these parameters, the greater the dual-task performance decline should be, because it is more difficult to effectively share attention between them. For example, it should be more difficult to divide attention between two visual tasks, than a visual and auditory task. This is because the former overtaxes the visual resources, but the latter can draw from two independent resource pools.

Researchers have also found evidence for separate information processing systems in short term memory, which contributed to the development of the working memory model (Baddeley & Hitch, 1974). Baddeley suggests that the working memory is composed of a phonological store, an articulatory loop, a visuospatial sketch-pad, and a central executive (Baddeley, 1992). In addition, he revised the model to include the episodic buffer, a temporary and limited capacity storage system useful for multimodal information (Baddeley, 2000, 2003). Therefore, working memory theorists may make predictions similar to those of the MRT regarding dual-task performance, but for the reason that people cannot actively attend to different simultaneous demands drawing on the same stores in working memory. Activities drawing on the different components of working memory, such as a spatial and a verbal task, should therefore show minimal interference. Guerard and Tremblay (2008) found that a verbal articulatory suppression task interfered more with a verbal memory task than a spatial memory task, and that a tapping task was more disruptive to a spatial memory task than a verbal memory task. PET research has also indicated that spatial and verbal tasks are processed in different brain regions, indicating not only functional but also physical dissociation (Smith, Jonides, & Koeppe, 1996). Other research, however, found interference across verbal and visual-spatial domains to be comparable to the interference within the domains (Jones, Farrand, Stuart, & Morris, 1995), supporting a more unitary model of memory than the working memory model suggested by Baddeley and Hitch (1974). This debate can be considered in parallel to the debate on unitary versus multiple resource perspective of human cognition, and requires further exploration. The working memory model's addition of the episodic buffer, which has its own storage capacity and is a useful multimodal component (i.e. information does not have to be strictly verbal or visual-spatial) intermediate to the long term memory, may help to link the attention and memory perspectives.

In previous work, Epling and colleagues (Epling, Blakely, et al., 2016; Epling, Russell, et al., 2016) utilized dual-task methodology to establish that performance on a verbally demanding free-recall task was impaired more by a simultaneous semantic discrimination task than various other non-verbal resource demanding tasks. Strangely enough, however, a climbing task (on several repetitions) interfered at least as much if not more than the semantic discrimination task on free recall (Darling and Helton 2014; Green and Helton 2011). Though it seems that the MRT has garnered vast support, it may not explain the entire story.

Why does climbing interfere with a verbal task more than Wickens' proposed matrix might suggest? Firstly, climbing may require more extensive cognitive resources overall, because efficient climbing requires constant monitoring of body orientation and planning a series of moves across the wall. This could suggest that a general pool of resources is a better explanation than the domain-specific pool of resources, or that an executive resource bottleneck exists. Alternatively, climbing could require more verbal resources than originally thought, in which case MRT would still be a viable explanation. There is a clearly established link between language and gesture, both neuro-anatomically and in practice, so perhaps the fact that climbers' upper limbs are otherwise occupied impairs their ability to adequately process the outside verbal demands of the memory task (Frick-Horbury & Guttentag, 1998; Wagner, Nusbaum, & Goldin-Meadow, 2004; Xu, Gannon, Emmorey, Smith, & Braun, 2009). Alternatively, climbers may plan their movements verbally via an internal monologue, even if the climbing itself occurs spatially.

A primary purpose of the present study was to help explain why climbing interferes with verbal recall to the extent that it does. Though pairing climbing itself with a purely spatial task such as tapping (Guérard & Tremblay, 2008; Jones et al., 1995) in place of the verbal recall task would be a logical approach to better understanding the resources that climbing requires, this presents implementation difficulties such as how to have rock climbers tap while also traversing the wall, along with how that would be measured. In addition, the growing list of research with the verbal recall task still has several interesting gaps to fill. So far there have been physically strenuous tasks both with and without planning requirements, seated tasks with and without verbal requirements, but so far no seated task with a planning requirement. The present research utilized a variant of the video game Tetris (Quadra, Figure 4-1), paired with the verbal recall task (Darling & Helton, 2014; Epling, Blakely, et al., 2016; Epling, Russell, et al., 2016; Green & Helton, 2011; Head & Helton, 2014b). Quadra has proven to be a useful research tool as it is a common game requiring little to no training, requires executive processing, is fast-paced, and is relatively fun for participants (Haier et al. 2009; Strang et al. 2011; Strang et al. 2013; Strang et al. 2014). In Quadra, participants are required to manipulate falling tetrominoes such that the pieces fit together, without gaps, at the bottom of the well. The Quadra game provides a seated alternative for the climbing task, in order to rule out the physically fatiguing and perceived risk components (fear of coming off the wall and resulting sympathetic nervous system arousal) as the cause of the greater dual-task interference. Like climbing, Quadra occupies the hands, and requires planning and constant updating of the situation as the pieces fall and the state of the board changes as rows disappear.

By further adding to the collection of research utilizing the same verbal recall task within the dual-task design, this research aims to shed more light on how and why the different relative amounts of interference occur. Dual-task research has been criticized for failing to have an independent measure of the resources required in each task, and therefore providing only a circular argument: though performance varies with resource demand and allocation, the resources specific to each task can only be inferred from performance (Navon, 1984). However, up until this point, holding one task constant while inserting different secondary tasks has not been frequently attempted – especially in an applied domain.

Participants performed Quadra in both a single-task condition and a dual-task condition where they performed the verbal recall task at the same time. Participants also performed the verbal recall task in a single-task condition. Reduced Quadra performance and reduced word recall performance were expected in the dual-task condition, compared to the respective single-task conditions. In addition to performance on both tasks participants reported subjective workload, and the dual-task was expected to require greater subjective workload than either task individually. The dual-task performance decline was then compared with previous research that employed the free recall task, to further evaluate the MRT. It was assumed that samples were comparable across studies due to being drawn from the same population.

4.3 Method

4.3.1 Participants

Fifty undergraduate psychology students (37 women) at the University of Canterbury served as participants for course credit. All participants had normal or corrected-to-normal vision, normal hearing, and were fluent English speakers based on self-report. Age of participants ranged from 17 to 56 years (*M* = 22 years, *SD* = 7.37). The study was approved by the University Human Ethics Committee, and informed consent was gained from each participant.

4.3.2 Materials

4.3.2.1 Word Recall Task

See Chapter 2 for details.

4.3.2.2 Quadra Task

Quadra, an open source Tetris variant, was adapted for use in this experiment. In Quadra, tetrominoes fall in a random sequence from the top of the playing field (the "well", see Figure 4-1) to the bottom. In the current experiment, the level of difficulty and rate at which the pieces fell (without participant input) was held constant (level 2). Participants have the ability to translate (left and right arrows) or rotate (up arrow, in 90 degree increments) the tetrominoes as they fall, in order to create horizontal lines of blocks without gaps. Participants also have the ability to speed the rate of fall by pressing the down arrow, or to make the block fall instantly to the bottom of the well by pressing the spacebar. Participants are also able to see which tetromino will fall next. Because the task runs for a set time, increasing the rate of fall would hypothetically enable participants to complete more horizontal rows in order to gain more points; however, participants were not given strategy suggestions for obtaining the greatest number of points. Each task in the experiment was also programmed to run for exactly five minutes. Therefore, if the well filled to the top by failing to complete rows, the well automatically cleared, allowing participants to continue the trial without reduction to their score.

To control for any effects of noise in the dual-task compared to Quadra-alone condition, a list of scrambled words (Green & Helton 2011) was played during the Quadra-alone task. The scrambled words were unrecognizable, and participants were told that there was no memory imperative (see Chapter 2 for further explanation).

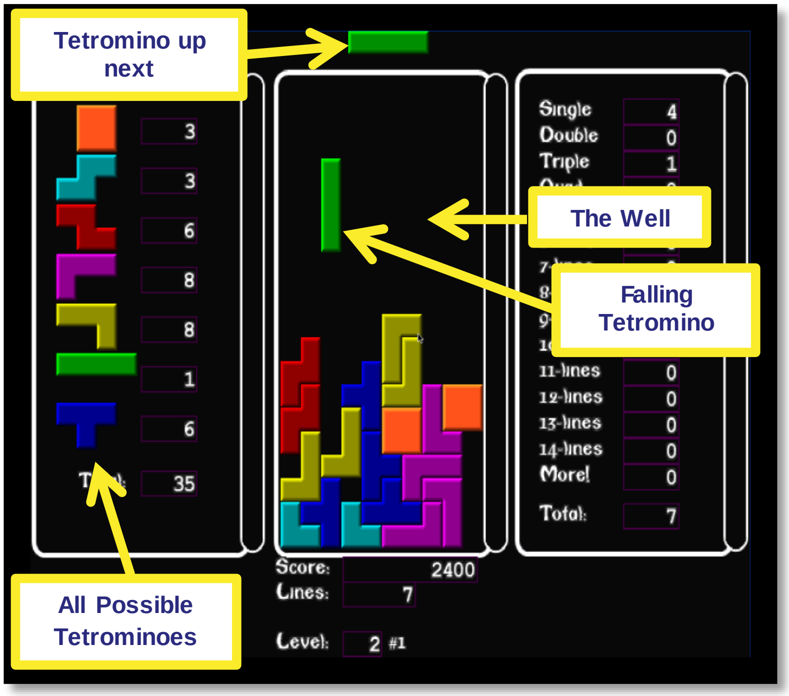

Figure 4-1. Annotated display of Quadra game, adapted from Strang et al. 2013.

4.3.2.3 Dual-Task

The five minute Quadra game was used again in the dual-task, along with the alternate 20-word list for the recall task. Which recall list was used in which task was counterbalanced among participants.

4.3.2.4 Questionnaire

A paper and pencil version of the NASA Task Load Index (TLX) (Hart & Staveland, 1988) was used. See Chapter 2 and Appendix C for details.

4.3.3 Procedure

Participants were tested at individual computer workstations within a larger psychology laboratory room at the University of Canterbury. Participants were run individually or in pairs seated on opposite sides of the room. Participants were unrestrained and seated approximately 50cm from eye-level screens (377 x 303 mm, 60 Hz refresh rate). Participants wore headphones and computer loudness was initially set at 30% intensity. Participants were shown how to adjust loudness to a comfortable level for themselves before beginning.

Participants were given verbal instructions on how to complete each task and were given the opportunity to ask questions. They were then given a two minute practice session on the Quadra game. If they had no further questions after the practice, they proceeded to the experiment. Participants were randomly assigned to one of six groups which counterbalanced the order of the three tasks and the two recall lists (within-participants design). The researcher manually started each task on the computer.

For the word recall task, participants heard one word every fifteen seconds, a total of 20 words in five minutes. Computer screens remained blank and participants were instructed to listen and remember as many words as possible. At the end of five minutes, participants were given one minute to write down all the words they remembered.

For the Quadra task, participants were asked to attempt the highest score possible by completing horizontal rows without gaps. They were told to use the arrows and spacebar on the keyboard to control the falling tetrominoes. During this task, participants heard 20 scrambled words with no memory imperative.

For the dual-task, participants performed another five minute game of Quadra, while listening to a different list of 20 words to remember. At end of the task, participants were given one minute to write down all the words they remembered.

At the end of each of the three tasks, participants filled out the NASA-TLX before proceeding to the next section.

4.4 Results

4.4.1 Word Recall

The number of words recalled in the single-task (word recall task alone) condition was higher ($M = 11.8$; $SD = 3.2$) than in the dual-task (word recall task while playing Quadra) condition ($M = 6.4$, $SD = 2.5$), $t(49) = 11.38$, $p < .001$, $M_{\text{difference}} = 5.4$ (95% CI [4.4, 6.3]). From the number of words recalled the percentage of information lost was calculated using the formula [(1-#words dual/# words single)*100], $M = 42.4$, $SD = 24.4$. This was compared to previous studies using this word recall task, and these comparisons are displayed in Figure 4-2.

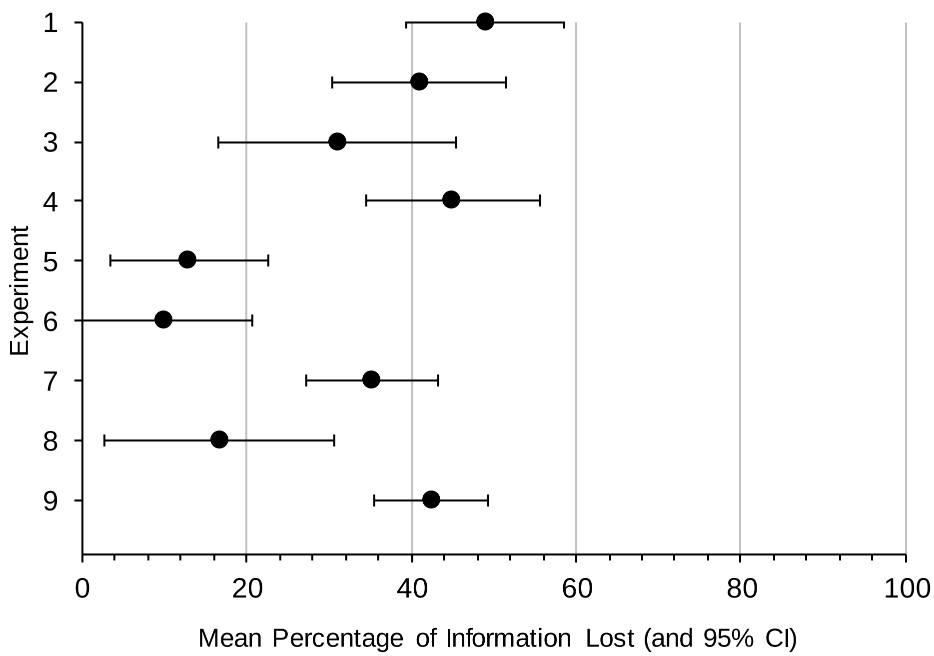

Figure 4-2. Mean percentage of information lost [(1 - # words recalled dual-task/# words recalled single-task) x 100] and 95% CI for nine experiments using the word recall task for the present study (experiment 9) and previous studies examining physical climbing (experiments 1-4; Darling & Helton, 2014; Green et al., 2014; Green & Helton, 2011; Woodham, 2015), seated manual control tasks (experiments 5 and 6; Head & Helton, 2014b; Ward & Helton, unpublished), semantic discrimination (experiment 7; Epling, Russell, et al., 2016), and running tasks (experiment 8; Epling, Blakely, et al., 2016).

4.4.2 Quadra

No significant difference was found between participants' Quadra scores in the single-task (Quadra only) condition (M = 7107.1, SD = 4539.9) and the dual-task (Quadra and recall) condition (M = 6659.4, SD = 4536.7), $t(49) = .83$, $p = .410$, $M_{\text{difference}}$ = 447.7 (95% CI [-635.0, 1530.4]). There was also no significant difference in Quadra score when comparing participants' first game of Quadra (either the single- or dual-task based on the counterbalance (M = 6563.7, SD = 4539.9) to second game (M = 7202.8, SD = 4625.4), $t(49) = 1.195$, $p = .238$, $M_{\text{difference}}$ = 639.1 (95% CI [-435.6, 1713.8]).

The overall score achieved in a condition divided by the total number of tetrominoes played in that condition was computed as an efficiency metric. There was no difference in efficiency between the single- (M = 92.53, SD = 47.33) and dual-task (M = 85.20, SD = 45.33), $t(49) = 1.063$, $p = .293$, $M_{\text{difference}}$ = 7.32 (95% CI [-6.53, 21.18]). There also was no significant difference in the raw number of tetrominoes used in each condition.

Only 21 of the 50 participants required a clearing of the well (due to filling it to the top) in one or both conditions. Among these 21, there was no significant difference between the number of wells used in the single- (M = 1.90, SD = .62) versus dual-task (M = 1.90, SD = .94), $t(20) = .000$, $p = 1.000$.

4.4.3 Subjective Workload

The average rating on each subscale of the NASA-TLX is shown in Table 4-1.

Table 4-1. Self-report averages on the TLX subscales

	Word Recall	Dual-Task	Quadra
Mental Demand	70.4(2.4)	79.3(2.3)	37.6(3.0)
Physical Demand	14.8(2.4)	25.5(3.4)	16.0(2.4)
Temporal Demand	36.2(3.0)	57.2(2.7)	34.8(3.1)
Performance	55.7(2.6)	61.4(3.2)	48.2(3.4)
Effort	69.8(2.5)	71.8(2.4)	43.2(3.2)
Frustration	45.5(3.8)	56.9(3.6)	29.6(3.3)
Average Workload	48.7(1.6)	58.7(1.7)	34.9(2.0)

Notes. Each value is the mean (standard error of the mean) self-report rating across all participants for that measure, on a scale of 0-100. The average workload rating is the mean of the six subscales.

An analysis of variance showed significant within-subject main effects of task on workload, $F(1.732,84.873) = 62.62$, $p < .001$, $\eta_p^2 = .561$. Mauchly's test indicated a violation of the sphericity assumption ($\chi^2(2) = 8.065$, $p = .018$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .866$). Pre-planned contrasts revealed that dual-task workload (M = 58.7, SD = 11.8) was greater than Quadra-alone workload (M = 34.9, SD = 14.1), $t(49) = 10.25$, $p < .001$, and recall-alone workload (M = 48.7, SD = 11.1), $t(49) = 6.00$, $p < .001$. The recall-alone workload was significantly greater than the Quadra-alone workload $t(49) = 5.88$, $p < .001$. Contrasts on the individual subscales revealed that effort was rated significantly higher on the dual-task (M = 71.8, SD = 16.9) than the Quadra-alone task (M = 43.2, SD = 22.5), $t(49) = 8.16$, $p < .001$, but not the recall-alone task (M = 69.8, SD = 17.6), $t(49) = .843$, $p = .403$. Effort on the recall-alone task was also significantly greater than effort on the Quadra-alone task, $t(49) = 7.035$, $p < .001$.

4.4.4 Verbal Recall Findings across various Secondary Tasks

The standardized effect sizes of the dual-task interference from previous studies using the same word recall task (Chapters 2 and 3 as well as previous work by other researchers, cited in Figure 4-2) were computed for comparison purposes. Only the studies using audio presentation of words without paired association were included so that the memory task was identical across experiments. This resulted in the removal of two studies using visual presentation of words via Google Glass (one for a seated tracking task, unpublished; one for a climbing task, Woodham et al., 2016) and one study using free association during climbing (Darling & Helton, 2014). Cohen's d_z was considered the most appropriate metric to compare within-subjects effects among each of the experiments. Cohen's d_z was computed two times for each experimental pair: once for the effect of remembering words on the "secondary" task (e.g., climbing, running, etc.) performance, and once for the effect of the secondary task on word recall performance. These data are found in Table 4-2, and can be visualized in Figure 4-3.

Table 4-2. Effect size of difference between single- and dual- task performance in the word recall task and various secondary tasks

Secondary tasks	Effect size(SE) of word recall decline from single- to dual-task	Effect size(SE) of *other* task performance decline from single- to dual-task
Climbing *(pooled data from Green & Helton 2011; Green et al. 2014)*	d_z = 2.292(.369)	d_z = .652(.117)
Sustained Attention to Response Task (SART; Head & Helton, 2014b)	d_z = .757(.207)	d_z = .456(.217)
Semantic Discrimination (Epling, Russell, et al., 2016)	d_z = 1.271(.192)	d_z = .701(.129)
Running (Epling, Blakely, et al., 2016)	d_z = .699(.247)	d_z = .367(.112)
Quadra *(present research)*	d_z = 1.609(.231)	d_z = .118(.118)

Notes. Standardized effect sizes, Cohen's d_z, with standard errors.

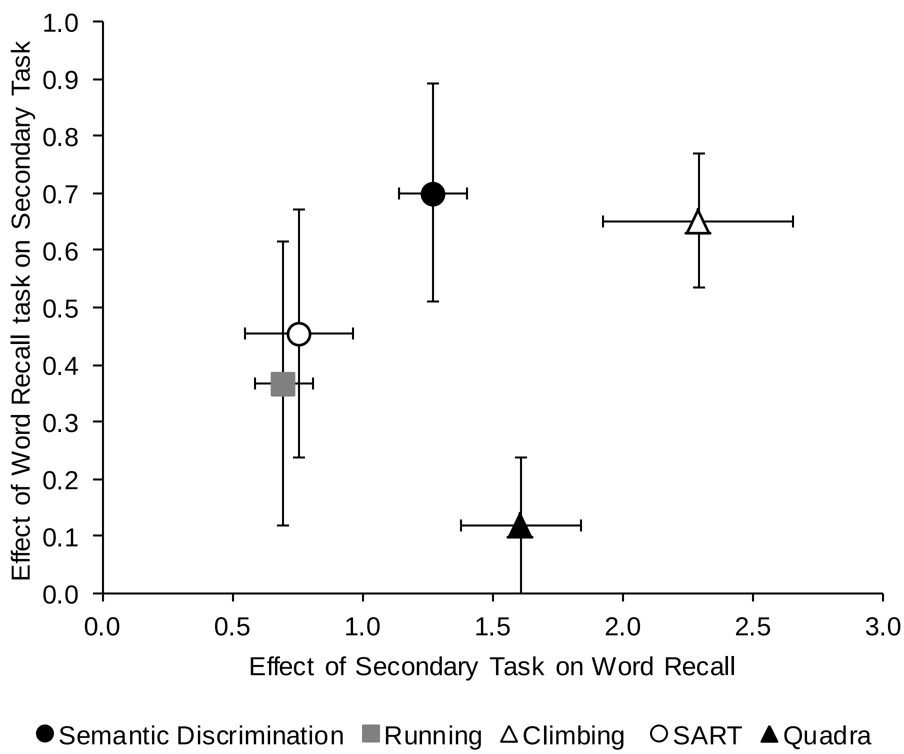

Figure 4-3. Standardized effect sizes (Cohen's d_z) for interference effect of different experimental tasks on word recall (x-axis) and the interference effect of the word recall task on those same experimental tasks (y-axis). The performance metric for the semantic discrimination task is d' (from signal detection theory), running and climbing are distance (meters), Quadra is raw game score, SART is errors of commission. Error bars are standard error of the mean for their respective dimensions. Only experiments using the audio word recall task, without free association, are included.

4.5 Discussion

The purpose of the current research was to expand on previous dual-tasking research using the verbal recall task to better understand why different levels of interference occur in different task pairs. By holding the verbal recall task constant across various secondary tasks, different levels of dual-tasking performance impairment can be used to map out different cognitive resources required by each task, and provide evidence regarding whether a unitary or multiple resource perspective of human cognition is more accurate. In particular, the Quadra task was chosen as a seated alternative to a previous climbing task. Like climbing, Quadra involves a spatial planning demand, but it does not have physical demand (or risk of coming off the wall). By comparing the present results to the climbing results, a better understanding of why climbing is so disruptive to verbal recall should be attainable.

In line with expectations, the significant reduction in word recall (i.e., information loss) was found in the dual-task condition compared to the recall-alone condition. Though Quadra is a visuospatial puzzle task, with no apparent verbal processing demand, it still impedes one's ability to remember a list of words. This is consistent with a general resource theory perspective, but not necessarily a multiple resource theory perspective (Wickens 2002, 2008). However, the executive resources required to plan the placement of tetrominoes may cause an information-processing bottleneck or general resource capacity overload, and thus any secondary task would have impaired performance, regardless of its specific resource demands. Additionally, because verbal processing is interconnected to physical hand gestures (Frick-Horbury and Guttentag 1998; Wagner et al. 2004; Xu et al. 2009), the occupation of one's hands on the Quadra task may exacerbate the reduction in word recall. Future research could incorporate a recall condition where the participants' hands are immobilized to explore this. Because word recall is substantially disrupted by the seated Quadra task, to a similar extent as climbing and a seated verbal task seen in Figure 4-2, this explanation seems plausible. Perhaps all planning is done in the same cognitive processing code (i.e., verbal) and this explains the interference (Paivio, 1991) and would be consistent with the MRT. The relative costs of different tasks should continue to be explored, to provide insight into the true structure of cognitive resources.

Inconsistent with hypotheses, participants' performance on Quadra did not differ significantly between the single- and dual-task conditions. There are several possible reasons for this. Firstly, the majority of participants were first year university students, 18-20 years old. It could be that people in general, or particularly this demographic, find computer games more engaging than trying to remember a list of random words, and therefore they focused more on Quadra than the word recall task, regardless of instructions not to prioritize either task. In Kahneman's (1973) discussion of the general capacity perspective of attention, he stated that the operator of a given set of tasks typically has control of which task to protect, at the sacrifice of the other, when there are not enough resources to successfully accommodate both. In addition, participants may have enjoyed the game so much that they attempted to improve their first game score during the second game of Quadra. Because of the counterbalance, this drive to improve (compounded by potential practice effects) could dilute any true score difference between single- and dual-tasks. If this research is repeated, participants should be given more than two minutes of practice on the Quadra game, and more explicit instructions regarding strategies to gain the highest score possible. The large variation in Quadra scores could also be behind a lack of significant dual-task effects. A median split was performed on the data, and further analyses are discussed in Appendix E. Finally, it should be noted that participants exerted significantly more effort in the dual-task condition in order to maintain performance.

Because the game was programmed to give participants a new, clear well should a well be filled to the top with tetrominoes, the number of wells used by each participant in each condition could be viewed as a measure of assistance needed during the game, and could potentially moderate the score achieved in dual- versus single-task conditions. However, few participants required this assistance, and among those who did, there was no more assistance used in the dual-task compared to single-task condition. There was also no difference in efficiency or number of total tetrominoes used, indicating consistent strategy and task urgency regardless of whether a second demand was imposed.

By looking at the effect sizes of dual-task interference from various experiments utilizing the same word recall task, some interesting patterns were discovered (see Figure 4-3). First and foremost, there is a notable difference in the interference effect in tasks that use different types of mental resources, which lends support to the MRT. For example, in the semantic discrimination task pair, more interference was found in both the discrimination and recall task than those in the running dual-task pair, and the SART dual-task pair (explanation of SART can be found in Chapter 9). In the semantic discrimination pair, both tasks required verbal resources, while the running and target selection tasks did not. Secondly, the effect size of the dual-task interference is never equivalent within a task on both dimensions, and the interference effect on word recall tends to be more severe than that on other task. In other words, the non-recall task always tends to be the “protected” task. For example, in Quadra, the large effect size of the word recall decline was roughly 1.6, while the effect size in the Quadra performance was not significantly greater than zero. In the climbing dual-task pair, which had a strong effect in both dimensions, a greater effect on word recall than climbing distance was observed.

Even though neither required apparent verbal resources, the climbing and Quadra tasks impaired word recall the most and second most respectively – even more than the semantic discrimination task did. This is inconsistent with a strictly structural perspective of human cognition, as the discrimination task requires continuous word processing. Though the comparisons above provide support for the MRT (e.g., though running is demanding it does not require the same type of resources as word recall, thus those tasks interfere less than the semantic discrimination and recall task), they also highlight the importance of considering executive bottlenecks and the general *amount* of resources required in addition to the specific *types* of resources required. The planning required by climbing and Quadra interfered with word memory the most, then the semantic discrimination task which draws from the same resources, and then the SART and running tasks interfere the least because they require neither domain specific resources (verbal), nor a great deal of general or executive resources. However, on the other dimension, the semantic discrimination decline in effect size was comparable to the climbing distance decline in effect size, and both were greater than all the other tasks – even Quadra. Yet again, the climbing task seems to be in a category of its own, as it behaves like the verbal task on one dimension, but like the planning task on the other dimension. This comparison lends support to the notion that climbing requires not only a planning component, but probably also a verbal component – due to the cognitive overlap between gesture and speech, or an actual internal monologue as participants plan their route across the wall.

The comparable levels of interference between recall with Quadra, and recall with climbing, may imply that the planning requirement is the major cause of interference. However, as is clear in Figure 4-3, climbing is uniquely challenging among the tasks investigated so far. This later finding may have real-world as well as theoretical implications. Psychologists and others may be underestimating the cognitive load of what would otherwise appear to be primarily a physical task. The general body of research that has been compared lends support to the MRT, with the caveat that the planning or executive demand of a task is also a very important consideration. Wickens does not discount this notion, but does not overtly include it in his structurally-focused model (Wickens, 2008).

In summary, the current visuospatial computer game Quadra was shown to be cognitively demanding, as it significantly interferes with performing a word recall task. This research adds to a growing matrix of dual-task pairings, helping to better understand the effects of dual-tasking when tasks do or do not overlap in underlying cognitive resources. The comparable levels of interference between recall with Quadra, and recall with climbing, may imply that the planning requirement is a major cause of interference. In the future, inserting different tasks into this dual-task paradigm will help to uncover a better understanding of the cognitive resource structure, and how to give weight to both the general and specific demands a task imposes. Also, the potential role of Baddeley's (2000) suggested episodic buffer should be incorporated into the analysis of the cognitive resource structure. The episodic buffer may help to accommodate the crossover between general and specific resources, as it holds information in a multimodal code and helps with the integration of information. In addition, utilizing both a visual-spatial (i.e., tapping with non-dominant hand) and verbal interfering (i.e., articulatory suppression) task with both the free recall task as well as the secondary task (wherever possible) would provide even more insight into the specific demands required of each individual task (Guérard & Tremblay, 2008; Jones et al., 1995).

5 Interference between Semantic Discrimination and Situation Awareness

5.1 Abstract

Resource theorists propose that the limited ability to perform multiple tasks simultaneously is due to a restricted supply of mental resources. The Multiple Resource Theory suggests that the more similar the tasks on certain parameters, the more interference and performance decline will occur. Military missions, firefighting, and search and rescue operations often present multiple high-risk tasks with both cognitive and physical demands, with limited insight into the specific demands and how they interfere. Regardless of the resource requirement of any task, these operators must also maintain the best possible situation awareness at all times. Attempting simultaneous tasks will divide and divert attention, but to what extent? The results of a dual-task study where a new situation awareness task is performed concurrently with the semantic discrimination task used in Chapter 2 is presented. As hypothesized, the semantic discrimination task caused significant performance degradation to the verbal resource-demanding situation awareness task. Based on these results, a continued use of the situation awareness task in new dual-task scenarios is suggested, to gain a better understanding of the mental demand in concurrent tasks required of the professionals listed above. This knowledge can be used to tailor the modality and timing or diversion of certain tasks for minimal interference.

5.2 Introduction

Awareness of one's surroundings is very important in high-risk, complex missions such as military operations, firefighting, and search and rescue. Situation awareness (SA) is the perception, processing, and projection of important information from the surrounding environment (Endsley & Garland, 2000). SA metrics aim to quantify the knowledge of the present state of affairs relevant to the goals and decision-making tasks at hand. Because SA is directly related to the probability of good decision making and performing well on a task (Endsley & Garland, 2000), the best possible SA is critical when the mission has life or death consequences.

The accuracy and comprehensiveness of the SA derived from an environment is influenced by several factors. The human operator is limited by working memory capacity and attention, and it is often impossible to adequately direct attention to all essential elements of a complex environment. Therefore, competing cues play an important role in determining what information will be processed to build SA. After the environment is perceived, the information must be integrated into the existing understanding of the situation, and considered in relation to future implications and goal outcomes. The continual attention, updating, and processing places great strain on working memory (Endsley & Garland, 2000).

Expectations can also affect SA. General knowledge, past experience, and mental models can lead to seeing or hearing that which is expected, rather than what is actually occurring. This incorrect SA can be even more dangerous than incomplete SA, for when the observer believes they have complete and correct SA they will not be attempting to fill in the gaps (Sallis, Catherwood, Edgar, Medley, & Brookes, 2013). This can lead to friendly fire accidents, where an ally is taken for an enemy despite ample evidence to the contrary, as well as driving accidents, where the driver may not process important danger warning cues, and countless other examples (Edgar & Edgar, 2007). In addition, people can be inherently biased towards more conservative or liberal responding in terms of deciding whether a certain cue is pertinent, as well as its severity (Catherwood, Edgar, Sallis, Medley, & Brookes, 2012; Edgar, Edgar, & Curry, 2003; Edgar & Edgar, 2007; Endsley & Garland, 2000).

SA has been studied and measured in a variety of ways, often including both subjective ratings and performance-based evaluations. SA researchers have even incorporated physiological monitoring in attempts to better understand the body's physiological manifestation of certain cognitive processes (Endsley & Garland, 2000; McKendrick et al., 2016). A relatively new approach is the Quantitative Analysis of Situation Awareness (QASA), which accounts for the important notion that false information may be stored alongside true information (Edgar et al., 2003). Thus, good SA according to the QASA technique is the ability to distinguish true from false information. SA can therefore be assessed by providing operators a list of probe statements about a given scenario, some true and some false, and applying Signal Detection Theory (SDT) metrics to extract an operator's SA based on their responses. For example, correctly identifying a true statement as true would be considered a hit, while identifying a false statement as true would be a false alarm. Edgar and colleagues (2003; Edgar & Edgar, 2007; Catherwood et al., 2012) compute A´ as a measure of the ability to distinguish true from false information, and B´´ as a measure of bias (how conservatively or liberally an operator tends to identify probes as true).

The resource theory is a common explanation for the limited ability to perform multiple tasks simultaneously, and suggests that the mental resources required for attention and information processing demands are limited but renewable. When these limited resources must be distributed among more than one task, they may be utilized faster than they are replenished, resulting in a decline in performance (Helton & Russell, 2015; Parasuraman & Mouloua, 1987). Because maintaining optimal SA loads attention and working memory, resource theorists would predict that any additional task required of the operators would not be performed as well as it could be if SA was not required, due to cognitive overload. The same holds true in the other direction; attempts to perform a second task should also harm SA.

Researchers have proposed both domain specific and domain general cognitive resources. Dual-task methodology is useful for exploring the resource theory (Caggiano & Parasuraman, 2004), and when one task is held constant across various secondary tasks, the task components causing the greatest interference become evident. Many studies have demonstrated worse performance in dual- compared to single-task conditions, regardless of the type of tasks used (Blakely, Kemp, et al., 2016; Bourke, 1996; Darling & Helton, 2014; Epling, Blakely, et al., 2016; Green & Helton, 2011; Head, Helton, et al., 2012; Head, Russell, et al., 2012), but it has been proposed that the more similar the demands of given tasks, the greater the detriment will be. The Multiple Resource Theory (MRT; Wickens, 2002, 2008), a specific sub-type of resource theory, proposes that the difference between single- and dual-task performance depends on the similarity of the tasks on any of four possible parameters: stage of processing (perception, cognition, or response), sensory modality (visual, auditory, or other), code of processing (spatial or symbolic), and for visual tasks, focal versus ambient vision. Thus, according to the MRT, the more similar two tasks are in terms of these parameters, the more dual-task cost or interference is to be expected. This greater interference or cost is because the specific resources necessary to perform both tasks are limited, but demanded by both tasks (Helton & Russell, 2011b, 2013, 2015). However, tasks requiring working memory require executive control and thus may divert resources from any secondary task regardless of overlap in the model. Wickens points out that any requirement for executive control will also impair dual-task performance (Chen & Cowan, 2009; Cowan, 2011; Wickens, 2002, 2008).

Recent research has shown that performing a word recall task concurrently with a semantic discrimination task caused noteworthy performance degradation in both tasks (Chapter 2; Epling, Russell, et al., 2016), as they both require verbal resources. In contrast, performing the word recall task while running over flat natural terrain caused less interference (Chapter 3; Epling, Blakely, et al., 2016).

Somewhat surprisingly, a climbing task caused at least as much, if not more interference as the semantic task, despite not requiring obvious verbal resources (Darling & Helton, 2014; Green & Helton, 2011). In the present study the semantic discrimination task from Chapter 2 was paired with a new SA task in place of the word recall task. Though verbal resources are still required to process the narrated situation, memory of the scenario cannot be achieved through rote repetition rehearsal. In the previous studies, the free recall word task used required verbatim recall, whereas the SA method used in the present study requires episodic or narrative memory for an accurate determination of whether particular events did or did not occur during the scenario.

The SA scenarios and probes were developed in accordance with the QASA technique (Catherwood et al., 2012). The dual-tasking paradigm has been frequently utilized to quantify the interference found when two specific tasks are performed simultaneously, but holding one task constant while inserting different secondary tasks has not been frequently attempted. Even less literature is available on dual-tasking in the real world physical task domain. In this report, the researcher aims to introduce and validate a useful new SA task to employ in the dual-task paradigm, in order to continue expanding the matrix of dual-task pairings. By pairing one task with several other tasks, the particular resources and their relative contributions to dual-task interference effects should be ascertainable. Because the SA task requires verbal resources, similar to the word recall task discussed above, significant interference from the semantic discrimination was expected, based on the MRT and previous research (Blakely, Kemp, et al., 2016; Epling, Blakely, et al., 2016; Epling, Russell, et al., 2016; Head, Helton, et al., 2012; Head, Russell, et al., 2012; Wickens, 2008). Performance on both tasks in the dual-task condition was expected to be worse than performance in the respective single-task conditions.

In this study participants had to classify briefly displayed and low visually discriminable words as naming either living or nonliving things, using the semantic discrimination task from Chapter 2. Participants performed this task in both a single-task condition, and a dual-task condition where they performed the SA task at the same time. The SA task required participants to listen to a narrated scenario with the knowledge that a memory test (a True-False measure of SA) on the scenario would follow the listening segment. Participants also performed the SA task alone in a single-task condition. As both tasks required verbal resources, reduced SA and reduced discrimination performance were expected in the dual- compared to both single-task conditions.

5.3 Method

5.3.1 Participants

Thirty-five undergraduate psychology students (27 women) at the University of Canterbury participated as part of requirements for course. All participants had normal or corrected-to-normal vision, normal hearing, and were fluent English speakers based on self-report. Age of participants ranged from 15 to 30 years (M = 21 years, SD = 4.0). The study was approved by the University Human Ethics Committee, and informed consent was gained from each participant.

5.3.2 Materials

5.3.2.1 Situation Awareness Task

Two audio fireground scenarios were developed, presenting a simulation of members of the public involved in a building fire. The scenarios were designed to be audio analogues of visual scenarios that have been successfully developed and tested with both firefighters and non-firefighters (Catherwood et al., 2012). The two scenarios were of the same duration (four minutes, thirty four seconds) and contained enough information for 24 true/false statements to be presented for each. All statements were unambiguously true or false with respect to the scenario and the probes related, as far as possible, to events evenly spaced throughout the scenario. Examples of probe statements used are: ‘The smoke alarm was broken’ and ‘The people were on the 5th floor when the fire broke out.’ Silence was added to the beginning and end of each audio track so that each track lasted five minutes. A response grid (Figure 5-1) accompanied each set of probe statements to facilitate true/false scoring and associated confidence ratings. Over the ear headphones were worn throughout the duration of the task.

Probe #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	P#
True																									**T**
False																									**F**
Guess																									**G**
Fairly uncertain																									**F un**
Fairly certain																									**F cer**
Certain																									**cer**

Figure 5-1. The probe response grid, which appeared below the list of 24 probe statements.

5.3.2.2 Semantic Discrimination Task

The task created for the experiment in Chapter 2 (see section 2.3.2.2 for details) was used in the present experiment without alterations. The focus in this chapter was not on the vigilance outcomes but merely the interference found in the dual- compared to single-task conditions.

5.3.2.3 Dual-Task

The second target-neutral list created for the discrimination task was used here along with the second audio scenario for the SA task. The pairings of discrimination word lists and SA scenarios were counterbalanced across participants.

5.3.3 Procedure

Participants were tested at individual computer workstations within a larger psychology laboratory room at the University of Canterbury. Participants were run individually or in pairs seated on opposite sides of the room. Participants were unrestrained and seated approximately 50cm from eye-level screens (377 x 303 mm, 60 Hz refresh rate) and wore the provided headphones for the duration of the experiment. Computer loudness was set at approximately 30% intensity for all participants, and it was confirmed that this was a comfortable loudness after the practice session. Stimulus presentations (both audio and visual) and recordings of reaction times and accuracy were executed by PC computers using E-Prime Professional 2.0 (Schneider et al., 2002).

Participants read instructions on how to complete the experiment and were given the opportunity to ask questions. They were then given a 100 second practice session on the discrimination task where they heard performance feedback on hits and misses. If they had no further questions after the practice, they proceeded to the experiment. Participants were assigned to one of six groups which counterbalanced the order of the three tasks (SA alone, discrimination alone, dual) in a within-subjects design.

For the SA task, participants merely listened to the scenario. Computer screens remained blank and participants were instructed to remember as much as possible. At the end of five minutes, participants were given as much time as needed to complete the true/false assessment.

For the discrimination task, participants were asked to monitor the computer screen and respond to living words with the spacebar, and withhold response to non-living words. See Chapter 2 for full description of task parameters. During this task, participants heard 20 scrambled words with no memory imperative.

For the dual-task, both of the above tasks were run simultaneously. Participants heard a new scenario to remember, while also responding to the discrimination task. At the end of five minutes, participants were given the SA true/false assessment.

5.4 Results

5.4.1 Situation Awareness

Each SA questionnaire had 24 probes: one scenario had 10 true and 14 false probes, and the other scenario had 12 true and 12 false probes. Participants gave a true or false response to each probe and indicated their confidence on each response using the following scale: guess, fairly uncertain, fairly certain, or certain (scored 1-4 respectively). For each participant the number of correct probe responses (correct detections) were scored, and the proportion of hits and false alarms was calculated for each task (single- and dual-task). The signal detection theory metrics of A´ (sensitivity) and B´´ (bias) were then calculated from these proportions using the process described by Edgar and colleagues (2003). The average confidence for each participant in each task was also calculated as a measure of perceived SA.

Participants responded correctly to significantly more probes in the single- (M = 17.3, SD = 2.10) compared to dual-task (M = 15.3, SD = 2.59) condition, $t(34)$= 4.71, $p < .001$, $M_{\text{difference}}$ = 2.0 (95% CI [1.15,2.90]). For correct detections, participants made a significantly greater proportion of hits in the single- (M = .773, SD = .126) compared to the dual-task condition (M = .708, SD = .109), $t(34)$ = 2.79, p = .009, $M_{\text{difference}}$ = .065 (95% CI [.017,.112]). Participants also made a significantly lower proportion of false alarms in the single- (M = .320, SD = .139) compared to the dual-task condition (M = .424, SD = .183), $t(34)$ = 3.77, p = .001, $M_{\text{difference}}$ = .104 (95% CI [.048,.160]).

For A´, participants had significantly higher sensitivity to true probes in the single-task (M = .809, SD = .086) than the dual-task (M = .708, SD = .139), $t(34)$ = 4.36, $p < .001$, $M_{\text{difference}}$ = .101 (95% CI [.054,.148]). Cohen's d_z, was calculated for this difference in order to compare dual-task interference across different experimental task pairs, d_z = .737 (95% CI [.317,1.157]).

For B´´, participants showed no significant difference in bias in responding between the single- (M = -.137, SD = .283) and dual-task conditions (M = -.061, SD = .233), $t(34)$ = 1.39, p = .172. Participants were significantly less confident about their responses (lower perceived SA) in the dual- (M = 2.80, SD = .51) compared to single-task (M = 3.15, SD = .41), $t(34)$ = 4.03, $p < .001$, $M_{\text{difference}}$ = 0.35 (95% CI [.17,.52]).

5.4.2 Semantic Discrimination

For each participant the proportion of correct detections, the proportion of false alarms, and the mean reaction time were calculated for the discrimination-alone task (single) and discrimination with SA-task (dual). These raw proportions were analyzed using t-tests for hits and false alarms. The primary focus was whether there was an overall difference in performance between the single- and dual-task conditions.

For correct detections, participants made a significantly greater proportion of hits in the single- (M = .660, SE = .028) compared to the dual-task (M = .617, SE = .030), $t(34)$ = 2.08, p = .045, $M_{\text{difference}}$ = .043 (95% CI [.001,.084]), Cohen's d_z = .352 (95% CI [.107,.597]).

A significant difference in false alarms was not found between the dual-task (M = .039, SE = .009) and the single-task (M = .036, SE = .005), $t(34)$ = .643, p = .524. There also was no significant difference in mean reaction time between the single-task (M = 704.02ms, SE = 9.25) and the dual-task (M = 708.95ms, SE = 11.55), $t(34)$ = .535, p = .569.

5.5 Discussion

In line with expectations, performance (proportion of hits) on the discrimination task was worse in the dual-task compared to the single-task. Various metrics (number correct, proportion of hits, proportion of false alarms, and A´) demonstrated that performance on the SA task was also worse in the dual- compared to single-task. Bias (B´´) was not statistically significantly different from the single- to dual-task, which is consistent with previous research indicating that individuals generally have a tendency towards one type of bias (liberal versus conservative), which may be a result of life experiences or personality traits (Catherwood et al., 2012; Catherwood, Sallis, Edgar, & Medley, 2011; Sallis et al., 2013). This means that participants are likely to be either liberal or conservative, but consistent in that tendency in both the single- and dual-task. It also makes sense that perceived SA is lower on the dual- compared to single- task, mirroring actual SA, though past research has found that actual and perceived SA do not always correlate (Catherwood et al., 2012; Sallis et al., 2013). Further discussion of this experiment in context with two other SA experiments can be found in the Chapter 7 discussion. Interference caused by the SA task compared to the verbal recall task on semantic discrimination and its implications will be discussed in Chapter 10.

6 Interference between Outdoor Running and Situation Awareness

6.1 Abstract

Multi-tasking situations are common in military, firefighting, search and rescue, and may other high risk operations. Cognitive and physical demands can occur at the same time, but little is known about the specific demands of real world tasks or how they might interfere with one another. Regardless of specific tasks in a mission, maintaining situation awareness – a multi-modal task in and of itself – is also essential for safety and mission success. The Multiple Resource Theory makes predictions regarding task interference based on how much the tasks overlap in certain parameters, for example verbal versus spatial, and auditory versus visual. The more similar the tasks, the more likely interference and performance decline will occur. It is well known that attempting simultaneous tasks will divide and divert attention, but to what extent? In this experiment, the situation awareness task used in the previous chapter was paired with an outdoor running task, and as expected, situation awareness performance declined when participants ran as fast as they could for five minutes, outdoors, while listening to the scenario. Based on the results of this study, it is suggested that a more cognitively demanding physical task, such as climbing, be paired with the situation awareness task for further development of the dual-task interference matrix.

6.2 Introduction

Though the Multiple Resource Theory (MRT) has gained support in a variety of domains, the specific cognitive demands of many real-world, physically strenuous tasks are elusive. Physical effort is not one of Wickens' parameters, and the specific cognitive demands of physical tasks are not clear, making it difficult to anticipate the potential interference they might cause. Though exercise of specific intensity and duration is shown to enhance performance on certain implicit cognitive tasks (Dietrich & Audiffren, 2011; Etnier et al., 1997), the effect on tasks that require greater executive resources has been inconsistent (Labelle et al., 2013). Even the seemingly straightforward effects of physical tasks on simple cognitive tasks may not hold true in more applied contexts, because the research is typically done with cyclical, laboratory-based physical tasks. Running on a treadmill and stationary cycling require very little, if any, executive processing or decision making (Whelan, 1996). These studies therefore may not be appropriate for understanding physical activity in more applied settings, where the physical tasks are more mentally challenging. These laboratory physical tasks may require fitness and physical effort, but they do not (or only minimally) require navigation, planning, obstacle avoidance, or situation awareness (SA). This experiment therefore uses a more realistic outdoor running task paired with a recently developed SA task (see Chapter 5 for more background on SA and the MRT).

Recent research has shown that performing a word recall task while running over flat, natural terrain caused a reduction in word recall (Chapter 3; Epling, Blakely, et al., 2016), but the interference was less than when paired with a semantic discrimination task (Chapter 2; Epling, Russell, et al., 2016). In the present study the running task (Chapter 3) was repeated along with the SA task (Chapter 5), to further expand the growing dual-task matrix using task pairs of various mental and physical requirements. Holding one task constant while inserting different secondary tasks and in this case, repeating the process again with a different primary task, helps avoid the circular argument by which task resources can only be assumed based on performance metrics (Navon, 1984). In addition, meager literature is available on dual-tasking in the real world physical task domain. In this experiment the new SA task is paired with an outdoor running task that is more operationally relevant than traditional indoor treadmill tasks, with the aim of seeing how maintenance of SA in a somewhat more realistic environment might be impeded by concurrent physical demands.

By testing the SA task against several secondary tasks, the aim is to at least partially identify particular resources and their relative contributions to dual-task interference effects. Because the SA task requires verbal resources, similar to the word recall task used in Chapters 2-4, less interference was expected from the running task than was found in the semantic discrimination (Chapter 5), based on the MRT and previous research (Blakely, Kemp, et al., 2016; Epling, Blakely, et al., 2016; Epling, Russell, et al., 2016; Head, Helton, et al., 2012; Head, Russell, et al., 2012; Wickens, 2008). However, some interference from running was still expected, based on the results from Chapter 3. In general, performance decrements on both running and SA tasks in the dual- compared to single-task conditions are expected.

In this experiment, participants completed a flat track outdoor running task (Blakely, Kemp, et al., 2016; Epling, Blakely, et al., 2016). Participants performed this task in both a single-task condition, and a dual-task condition where they performed the SA task at the same time. Participants also performed the SA task in a single-task condition. As the running task required high physical load but no overt semantic resources, reduced SA and less distance run in the dual- compared to both single-task conditions were expected. A subjective stress state questionnaire was also administered after each task. The spent component, task focus component, and overall workload of the dual-task condition were expected to be greater than both single-task conditions. The run-alone condition was also expected to have the lowest task focus as a verbal cognitive task should reduce the capacity for task unrelated thoughts, and the two conditions involving a run were expected to have a greater spent component than the cognitive task alone.

6.3 Method

6.3.1 Participants

Twelve athletes (4 women) recruited in the general Christchurch region participated in this research. Participants were required to be physically fit (exercising a minimum of three days a week), healthy, fluent English speakers, and to have normal vision and hearing. Age of participants ranged from 20 to 41 years (M = 26 years, SD = 5.0). The study was approved by the University of Canterbury Human Ethics Committee, and informed consent was gained from each participant. All participants received a $10 voucher to a local shopping mall as compensation for their time. Participant demographics and fitness related statistics are presented in Table 6-1.

Table 6-1. Participant demographics and fitness information

Participant	Gender	Age	Weight(kg)	Height(m)	BMI	PA-R	VO_2max^1	VO_2max^2
1	Male	23	64.7	1.69	22.65	7	55.3	55.0
2	Female	24	63.6	1.74	21.01	6	42.7	42.9
3	Female	41	60.9	1.63	22.92	7	46.9	36.9
4	Male	26	69.8	1.76	22.53	7	56.5	53.9
5	Male	29	73.2	1.75	23.90	6	53.0	49.8
6	Male	26	86.0	1.82	25.96	6	49.2	49.4
7	Female	25	71.1	1.71	24.32	6	40.2	40.0
8	Male	26	70.7	1.70	24.46	5	49.7	48.6
9	Female	20	52.0	1.59	20.57	6	44.1	44.8
10	Male	23	70.1	1.70	24.26	7	50.9	53.7
11	Male	26	78.9	1.72	26.67	6	49.3	48.9
12	Male	23	75.7	1.85	22.24	5	52.1	51.4

Note. BMI is given by weight (in kilograms) divided by squared height (in meters). PA-R comes from the physical activity questionnaire used with the Jackson Non-Exercise Test. VO_2max^1 was calculated from the 1-mile jog test, VO_2max^2 was calculated from the Jackson Non-Exercise Test, see Appendix B.

6.3.2 Materials

Participants wore their own running gear and the provided helmet (Specialized adult cycling helmet) for safety. Over-the-ear headphones (Kama Triton) were attached to the helmet. Participants wore a heart rate monitor (Polar RC3 GPS), and carried an IPod (model A1367) in hand during the task. A digital scale was used to obtain participants' weights (Tanita BC-532 Inner Scan Body Composition Monitor), a measuring tape and wall to obtain height, golf markers and a surveyor's wheel to mark and measure the distance run, and a stopwatch to record mile time and determine when tasks were complete.

6.3.2.1 Situation Awareness Task

See Chapter 5 for details.

6.3.2.2 Running Task

This experiment was conducted outdoors on a flat 400m oval grass track at a local school. Participants were run one at a time and were scheduled with an attempt to maintain consistent conditions, including dry weather and short grass height. The same starting line was used for each participant, and an extra 9.3 meters was marked for the fourth lap of the one-mile run.

6.3.2.3 Dual-Task

The running task was done while listening to the scenario for the SA task. The particular scenario participants heard in the single- versus dual-task condition was counterbalanced.

6.3.2.4 Questionnaire

The subjective stress state questionnaire was used (see Chapter 3 and Appendix D for details).

6.3.3 Procedure

Participants met the researcher on the sidewalk leading from the street to the track, where they were given an information packet on the purpose and procedure for the task, an informed consent document to sign, biographical details to report, and an exercise rating questionnaire. Participants were given the opportunity to ask questions. Once consent was given, height and weight measurements were taken, and then the participant and researcher proceeded to bleachers near the track.

Participants were told how to put on a chest strap heart rate monitor along with the watch to display heart rate in real time. Participants took a seat on the bleachers while they were given more instructions, allowing heart rate to return to rest. Participants were told that they would begin with a one-mile warm-up jog, which would be used to estimate their VO_2 max (see Appendix B). They were told to go at a consistent and easy pace (slower than eight minutes for men and nine minutes for women). They were told that they would get an update of their time after each 400m lap. Participants' resting heart rates were recorded, and if there were no further questions, participants proceeded to the start line. Participants were instructed to begin running whenever they were ready, and the stopwatch was started when they began running. After completing a mile, participants' time and heart rate were recorded.

Participants were asked to take a seat and were allowed water. They were told that they would next be doing three different tasks: a five minute seated SA task, a five minute run, and a five minute run with SA task (dual-task condition). Participants were allowed water and rest between each task, and were required to wear the helmet/listening apparatus for the duration of the experiment. This was a within-subjects design, and participants were randomly assigned to all possible orders for the three tasks.

Participants were instructed to run as far as they could around the track in the five minute running task. They were told the experimenter would begin running near them towards the end of the task to mark their distance at exactly five minutes, but not to change their effort or stop until told. This method was chosen from previous research (Blakely, Kemp, et al., 2016; Epling, Blakely, et al., 2016). A stopwatch was used to time the task and a golf marker was used to mark the distance the participant had reached at five minutes. A golf marker was used so that the experimenter could measure the exact distance run at the end of the experiment, but so that the distance was not visually salient to the participant. The researcher was positioned near the participant just before the time was up and began running with the participant in order to see where the foot was placed precisely at five minutes. The participant was told to stop running, the marker was placed, and heart rate was recorded. Distance was measured with the surveyor's wheel at the completion of all tasks. During the run-alone task, participants heard the scrambled scenario for control. The correct audio file was queued on the IPod, and participants pressed play as they began running. The volume was set at three quarters of max intensity but participants were allowed to adjust it.

For the SA task, participants were instructed to sit on the bleachers and to listen to the scenario. The researcher cued the audio file on the IPod, and participants were told to press play when ready. At the end of five minutes, participants filled out the SA assessment.

For the dual-task, both of the above tasks were performed simultaneously. Participants heard the alternate SA scenario while also running as far as they could in five minutes. At the end of the task, participants were given a clipboard and time to complete the SA assessment.

At the end of each task, heart rate was recorded by the researcher within five seconds. Participants also filled out the subjective stress scale and were given time to rest before proceeding to the next task. Participants were encouraged to rest until they felt sufficiently refreshed to proceed to the next task.

6.4 Results

6.4.1 Situation Awareness

Participants had more correct responses in the single- (M = 18.0, SD = 2.3) compared to dual-task (M = 16.4, SD = 2.0) condition, but the difference just failed to reach significance, $t(11) = 2.16$, $p = .054$,

$M_{\text{difference}}$ = 1.58 (95% CI [-.03,3.20]). For correct detections, participants made a significantly greater proportion of hits in the single- (*M* = .80, *SD* = .07) compared to dual-task condition (*M* = .70, *SD* = .09), *t*(11) = 2.44, *p* = .033, $M_{\text{difference}}$ = .10 (95% CI [.01,19]). No significant difference in false alarms was found (single *M* = .29, *SD* = .14; dual *M* = .34, *SD* = .18), *t*(11) = .92, *p* = .380.

For A´, participants had significantly greater sensitivity to true probes in the single-task (*M* = .830, *SD* = .086) than the dual-task (*M* = .766, *SD* = .080), *t*(11) = 2.34, *p* =.039, $M_{\text{difference}}$ = .064 (95% CI [.004,.125]), Cohen's d_z = .676 (95% CI [-.030,.1.382]). Participants showed no significant difference in bias (B´´) in responding between the single- (*M* = -.010, *SD* = .170) and dual-task conditions (*M* = .043, *SD* = .283), *t*(11) = 1.47, *p* = .170. Participants were significantly less confident about their SA in the dual- (*M* = 2.80, *SD* = .40) compared to single-task (*M* = 3.16, *SD* = .34), *t*(11)= 2.42, *p* = .034, $M_{\text{difference}}$ = .36 (95% CI [.03,.69]).

6.4.2 Running

Participants did not run quite as far in the dual-task (*M* = 1133.7 m, *SD* = 176.0) compared to the single-task condition (*M* = 1147.0 m, *SD* = 173.5) as seen in Figure 6-1, but the difference was not significant, *t*(11) = 1.26, *p* = .234, $M_{\text{difference}}$ = 13.33 m (95% CI [-9.97,36.64]), Cohen's d_z = .364 (95% CI [.171,.557]). There was no significant difference in heart rate at the end of the single-task run (*M* = 186.0 bpm, *SD* = 9.14) compared to the dual-task run (*M* = 185.7 bpm, *SD* = 10.48), *t*(11) = .283, *p* = .782.

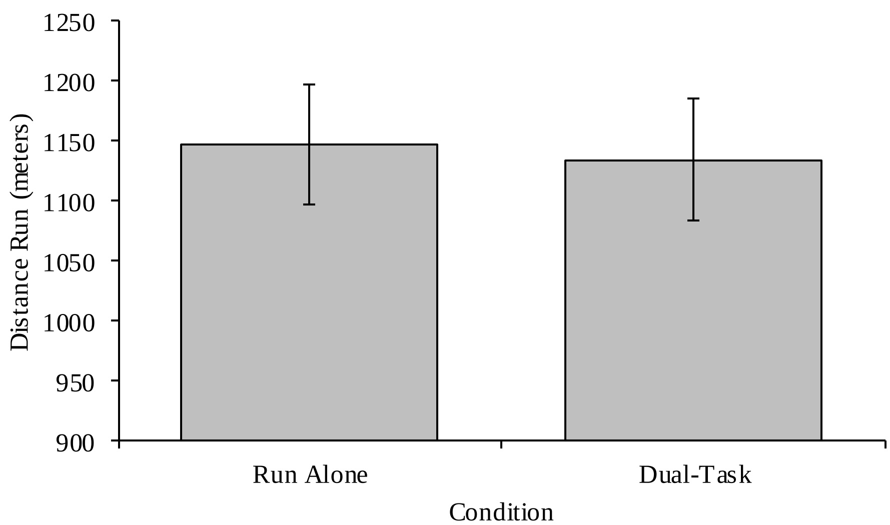

Figure 6-1. Average distance run in run alone (single-task) versus dual-task conditions. Error bars show standard error of the mean.

6.4.3 Subjective Stress State

The average ratings on the self-report scale are shown in Table 6-2. An analysis of variance showed no significant within-subject main effects of task on workload, *F*(1.24,13.64) = 3.17, *p* = .091,

$\eta_p^2 = .224$. Mauchly's test indicated the a violation of the sphericity assumption ($\chi^2(2) = 9.49$, $p = .009$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .620$). An analysis of variance did show significant within-subject main effects of task on spent component, $F(2,22) = 7.17$, $p = .004$, $\eta_p^2 = .395$, and task focus component, $F(2,22) = 12.51$, $p < .001$, $\eta_p^2 = .532$. The sphericity assumption was not violated in the spent nor task focus analysis.

Table 6-2. Self report averages

	SA Alone	Dual-Task	Running Alone
Mental Demand	53.8(8.1)	67.5(6.4)	28.3(4.8)
Physical Demand	2.9(1.1)	72.1(4.2)	77.1(3.6)
Temporal Demand	17.5(7.2)	52.5(5.8)	62.9(5.1)
Emotional Demand	23.8(6.8)	30.8(6.3)	31.3(6.9)
Performance Monitoring Demand	34.2(9.6)	62.1(7.6)	50.0(7.3)
Effort	93.8(56.4)	72.1(6.4)	78.8(3.1)
Physical Fatigue	9.6(3.7)	68.8(6.7)	72.9(4.1)
Mental Fatigue	29.6(6.3)	43.3(5.8)	24.6(5.5)
Tense	32.3(8.8)	37.5(5.6)	29.6(4.4)
Unhappy	26.7(7.9)	21.3(5.5)	23.3(5.6)
Motivation	62.9(6.8)	70.4(4.9)	69.2(4.7)
Task Interest	63.8(6.5)	67.9(6.0)	35.8(6.4)
Self Related Thoughts	21.7(6.3)	32.9(8.1)	57.9(6.3)
Concentration	73.3(4.9)	75.4(5.5)	59.6(4.2)
Confidence	63.3(6.5)	54.2(5.5)	59.2(6.4)
Task Related Thoughts	77.1(5.2)	77.9(4.6)	60.8(5.7)
Task Unrelated Thoughts	26.7(6.6)	21.7(5.6)	45.8(5.8)
Workload	37.6(10.6)	59.5(4.0)	54.7(2.2)
Spent	26.8(5.3)	43.3(3.9)	38.3(2.3)
Task-Focus	73.0(3.5)	73.8(3.2)	57.2(3.0)

Note. Each value is the mean (standard error of the mean) self-report rating on the subjective stress state questionnaire across all participants for that measure, on a scale of 0-100.

Because of the interest in the difference between single- and dual-task performance, planned contrasts were conducted. The spent component was greater in the dual-task ($M = 43.3$, $SD = 13.6$) than the SA-alone task ($M = 26.8$, $SD = 18.2$), $t(11) = 3.69$, $p = .004$, $M_{\text{difference}} = 16.6$ (95% CI [6.7,26.5]). The spent component was also significantly greater in the run-alone ($M = 38.3$, $SD = 8.0$) than the SA-alone task, $t(11) = 2.21$, $p = .049$, $M_{\text{difference}} = 11.5$ (95% CI [.1,22.9]).

Task focus was greater in the dual-task condition ($M = 78.8$, $SD = 11.1$) than the run-alone task ($M = 57.2$, $SD = 10.2$), $t(11) = 5.06$, $p < .001$, $M_{\text{difference}} = 16.67$ (95% CI [9.4,23.9]). Task focus was also greater in the SA-alone task ($M = 73.0$, $SD = 12.1$) than the run-alone task, $t(11) = 3.66$, $p = .004$, $M_{\text{difference}} = 15.83$ (95% CI [6.3,25.4]).

6.5 Discussion

Participants displayed better SA (A´, or sensitivity to true probes) in the seated single-task than the dual-task. While participants did not run as far in the dual-task as the run-alone condition, the difference in distance failed to reach statistical significance. This is in line with both a resource theory perspective of human cognition, and with previous research (Darling & Helton, 2014; Epling, Blakely, et al., 2016; Green & Helton, 2011) demonstrating that participants will likely preserve performance on a physical task relative to a cognitive task (Wickens, 2008). It is not surprising that participants' SA declines when they are required to perform a concurrent physically strenuous task. As predicted, this shows that running outdoors is, in fact, demanding of cognitive resources. In addition, self-reports of task focus and being "spent" were greater in the dual-task condition.

Participants were instructed not to prioritize either task, but running may nevertheless have been prioritized subconsciously because mistakes in a physical task could result in injury (Epling, Blakely, et al., 2016; Wickens, 2008). In addition, failure of the cognitive task in this scenario incurs little cost to the participant, whereas failing to achieve a distance goal during the run may cause unpleasant feelings. Unlike a real-world firefighting situation, maintaining SA was not critically important for safety, and the overall success of the dual-task "mission" did not have life or death consequences. Maintaining SA had little to do with the run itself, so in order to do their best on the run, participants may have inadvertently (or intentionally) shed the SA task, which supports the result that statistically significant performance impairments were found in the cognitive but not physical performance in the dual-task condition. In addition, though the dual-task is assumed to be cognitively more difficult, some runners perceive lower exertion and have greater endurance when not focusing on the run itself (Masters & Ogles, 1998). However, because the performance trend was in the anticipated direction, perhaps more sensitive measures or a larger sample size would have led to the detection of a significant dual-task reduction in the distance run.

Further discussion of this experiment in context with two other SA experiments can be found in the Chapter 7 discussion. Interference caused by the SA task compared to the verbal recall task on semantic discrimination and its implications will be discussed in Chapter 10.

7 Interference between Climbing and Situation Awareness

7.1 Abstract

The Multiple Resource Theory (MRT) proposes that the more structurally similar two tasks are on a set of certain cognitive dimensions, the more difficult it will be to successfully perform them simultaneously, due to a limited supply of specific mental resources. Military missions, firefighting, and search and rescue operations often present multiple high-risk tasks with both cognitive and physical demands, with limited insight into the specific task demands and how they overlap on the MRT parameters. Previous research found that dual-task performance impairments were much greater between a climbing traverse and verbal recall task than would be predicted solely by the MRT approach. In the current research, the same climbing traverse - representing a realistic, physically and mentally demanding task that might be done by search and rescue teams - was paired with the situation awareness task used in previous chapters. As hypothesized, the climbing task results were consistent with prior research, demonstrating that climbing requires deeper and more varied cognitive resources than that of a flat running task, resulting in significant dual-task performance impairments. The specific cognitive demands of climbing are still unclear, though the use of one's hands and an executive resource bottleneck may explain, in part, the notable dual-task interference. Based on these results, a more thorough investigation of the mental demand in concurrent tasks required in high-risk professions is suggested. This knowledge can be used to tailor the modality and timing or diversion of certain tasks for minimal interference.

7.2 Introduction

As mentioned previously, the specific cognitive demands of many real-world, physically strenuous tasks are elusive. Exercise science literature tends to study cognitive-physical dual-tasking effects using cyclical laboratory tasks (e.g., treadmill running, stationary cycling) which may not be representative of more cognitively demanding real world contexts. Studies such as these may be inappropriate for understanding physical activity in more applied settings, where the physical tasks involved are mentally more challenging. These laboratory physical tasks may require fitness and physical effort, but they do not require navigation, obstacle avoidance, and they involve little planning or situation awareness – in other words, there is minimal executive demand. In addition, Wickens' parameters do not provide predictions regarding how physical demand of tasks might cause cognitive interference. One aim of this study is to help better understand the utility of the MRT and whether it can explain the effects of physically strenuous tasks.

Recent research has shown that performing a word recall task concurrently with a semantic discrimination task caused noteworthy performance degradation in both tasks (Epling, Russell, et al., 2016), as they both require verbal resources. More surprising is that a climbing task caused at least as much if not more interference than the semantic task, despite not requiring obvious verbal resources (Darling & Helton, 2014; Green & Helton, 2011). In the present study the climbing task used in previous research was paired with the new situation awareness (SA) task featured in the two previous chapters.

This experiment tested whether a significant cognitive interference existed between the indoor rock climbing task and the SA task used in Chapters 5 and 6. It was predicted that poorer performance would result for both the climbing and SA tasks in the dual-task condition compared to the respective single-tasks. The three studies thus far that have used the SA task were then analyzed together in order to make comparisons based on relative dual-task interference. Because the SA task requires verbal resources, similar to the word recall task discussed above, more interference was expected from the semantic discrimination task than the running task, based on the MRT and previous research (Blakely, Kemp, et al., 2016; Epling, Blakely, et al., 2016; Epling, Russell, et al., 2016; Head, Helton, et al., 2012; Head, Russell, et al., 2012; Wickens, 2008). However, interference from the climbing task was expected to be more similar to that of the semantic task than the running task, despite climbing appearing to be more physical than verbal in nature, because past research has found climbing to be particularly disruptive to verbal free recall (Darling & Helton, 2014; Green et al., 2014; Green & Helton, 2011; Woodham et al., 2016).

7.3 Method

7.3.1 Participants

Twelve athletes (4 women) recruited in the general Christchurch region participated in this research. Participants were required to be physically fit (exercising a minimum of three days a week), healthy, fluent English speakers, and to have normal vision and hearing. All participants were required to have climbing experience. The minimum climbing grade that participants reported being able to climb was New Zealand grade 17 (indoor top-rope), ensuring that all climbers were at least intermediate level climbers or higher. Age of participants ranged from 19 to 30 years (M = 24 years, SD = 3.8). The study was approved by the University of Canterbury Human Ethics Committee, and informed consent was gained from each participant. All participants received a $10 voucher to a local shopping mall as compensation for their time. Participant demographics are presented in Table 7-1.

Table 7-1. Participant demographics and fitness information

Participant	Gender	Age	Weight(kg)	Height(m)	BMI	PA-R	VO_2max^2
1	Female	24	59.0	1.53	25.2	6	39.7
2	Male	26	75.4	1.78	23.8	7	53.0
3	Male	29	74.2	1.81	22.7	6	50.8
4	Female	25	57.3	1.67	20.6	7	44.8
5	Male	20	69.8	1.79	21.8	6	54.8
6	Male	27	65.3	1.63	24.6	7	52.0
7	Male	20	91.3	1.85	26.7	7	53.1
8	Male	20	73.0	1.76	23.6	7	55.4
9	Male	29	57.0	1.71	19.5	3	47.4
10	Male	30	84.1	1.84	24.8	7	50.6
11	Female	19	60.9	1.65	22.4	6	43.8
12	Female	23	60.1	1.68	21.3	7	45.0

Note. BMI is given by weight (in kilograms) divided by squared height (in meters). PA-R comes from the physical activity questionnaire used with the Jackson Non-Exercise Test. VO_2max^2 was calculated from the Jackson Non-Exercise Test, see Appendix B.

7.3.2 Materials

Participants wore their own preferred climbing gear. Standard grade (Manhattan) on-ear headphones were provided for the listening requirement, attached to an IPod (model A1367) during the task. A digital scale was used to obtain participants' weight (Tanita BC-532 Inner Scan Body Composition Monitor), a measuring tape and wall to obtain height. Participants wore a heart rate monitor (Polar RC3 GPS), and a stopwatch was used to determine when participants' five-minute climbs were complete.

7.3.2.1 Situation Awareness Task

See Chapter 5 for details.

7.3.2.2 Climbing Task

This experiment was conducted at the University of Canterbury Recreation Centre indoor climbing wall. The area of the wall used for the traverse was 8.25m in horizontal distance. Participants were not roped, and were required to stay below the 3.3m tape line marked as the maximum safe height for un-roped climbers. The wall was configured with varying sizes, shapes, and colors of holds. The floor around the wall was heavily padded to prevent injury. Participants were run through the experiment one at a time, and the room was reserved and sign-posted such that drop-in climbers would not disturb the task. A high resolution, widescreen webcam (Logitech C930e) mounted on a laptop was used to film the climbing components for later analysis. During the climbing tasks, the IPod was secured in a lightweight, unobtrusive runner's belt (Spibelt) around the waist. Attached to the belt was also a yellow plastic ball, used as a distinct target for later analysis of the video recordings. The belt was worn such that the yellow ball appeared in the center of participants' mid-back. This task was performed while listening to the scrambled audio scenario.

7.3.2.3 Dual-Task

Subjects listened to one of the SA task scenarios while climbing. The SA assessment was given immediately following the task. The particular scenario participants heard in the single- versus dual-task condition was counterbalanced.

7.3.2.4 Questionnaire

The subjective stress state questionnaire was used (see Appendix D and Chapter 3 for details).

7.3.3 Procedure

Participants met the researcher at the entrance to the Recreation Centre and were taken to the climbing wall. They were given an information packet outlining the purpose and basic instructions for the task, an informed consent document to sign, a questionnaire to report biographical details, and an exercise rating questionnaire. Participants were given the opportunity to ask questions. Once consent was given, participants were asked to remove their shoes and any heavy outer garments to take height and weight measurements.

Participants were given a chest strap heart rate monitor and instructed how to put it on themselves, along with the watch which recorded and displayed heart rate in real time. Participants were asked to take a seat facing the wall while they were given more instructions. This time also allowed heart rate to return to rest. A brief demonstration was given by the researcher, showing where, when, and how to mount the wall, where and how to turn-around, and what to do when the task was completed. Participants were told that the researcher would queue the correct recording on the IPod, and secure it into the belt. Participants would then place their left hand and left foot on the left wall. Upon hearing the audio track commence, they were to mount the main wall and begin their horizontal traverse, at which point the researcher would start the stopwatch and the video recording, as well as manually noting how many full traverses (and number of panels for partial traverses) the participant made. They were to move horizontally across the wall, covering as much horizontal distance as possible in the five minutes given. They were shown the 8.25m turn around point and were told that they needed to fully cross that line with their right hand and foot before heading back in the other direction. They were to keep going back and forth until told by the researcher that five minutes was up and they could dismount the wall. They were told that should they come off the wall at any point, they should attempt to remount the wall immediately in the same spot they came down.

Participants were told that they would next be doing three different tasks: a five minute seated SA task, a five minute climb (with the scrambled scenario), and a five minute climb with SA task (dual-task condition). Participants were allowed water and as much rest time as they needed between each task. This was a within-subjects design, and participants were randomly assigned to one of the possible set of orders for the three tasks. If participants had no questions, their resting heart rate was recorded and they were told how to commence their first task.

For the climb-alone task, participants were instructed to partially mount the wall (as demonstrated), and commence the climb with the beginning of the scrambled audio track and to traverse as far as possible in the given time. For the SA task, participants were instructed to sit on the padded floor and to listen and remember as much about the scenario as possible. At the end of five minutes, participants were given the SA assessment to complete. For the dual-task, both of the above tasks were performed simultaneously. Participants heard the second scenario while also climbing in the given time. At the end of five minutes, participants were given the SA assessment. At the end of each of the three tasks, after the SA assessment (when applicable) participants filled out the subjective scale.

7.4 Results

7.4.1 Situation Awareness

Participants had significantly more correct responses in the single- (M = 17.81, SD = 2.47) compared to dual-task (M = 14.33, SD = 3.20) condition, $t(11) = 2.70$, $p = .021$, $M_{\text{difference}} = 3.58$ (95% CI [.66,6.51]). For correct detections, participants made a significantly greater percentage of hits in the single-task (M = .779, SD = .108) than the dual-task (M = .647, SD = .145), $t(11) = 2.78$, $p = .018$, $M_{\text{difference}} = .132$ (95% CI [.027,.236]). Participants made a greater percentage of false alarms in the dual-

(M = .446, SD = .224) compared to single-task (M = .279, SD = .161), though this difference just failed to reach significance, $t(11) = 2.18$, $p = .052$, $M_{\text{difference}} = .167$ (95% CI [-.002,.336]).

For A´ participants had significantly greater sensitivity to true probes in the single-task (M = .829, SD = .086) than the dual-task (M = .648, SD = .145), $t(11) = 3.31$, p =.007, $M_{\text{difference}} = .181$ (95% CI [.061,.301]), Cohen's $d_z = .956$ (95% CI [.174,1.739]). For B´´, no significant difference was found in bias in responding between the single- (M = -.024, SD = .292) and dual-task conditions (M = .030, SD =.228), $t(11) = .522$, $p = .612$. Participants were significantly less confident about their situation awareness in the dual- (M = 2.36, SD = 0.37) compared to single-task (M = 3.02, SD = 0.44), $t(11) = 4.76$, $p = .001$, $M_{\text{difference}} = .66$ (95% CI [.35,.96]).

7.4.2 Climbing

Participants climbed farther in single- (M = 44.47m, SD = 20.05) compared to dual-task (M = 39.35m, SD = 16.47) condition, though statistically non-significant, $t(11) = 1.86$, $p = .090$, $M_{\text{difference}}$ = 5.12m (95% CI [-.94,11.18]), Cohen's $d_z = .537$ (95% CI [.182,.892]), seen in Figure 7-1. This difference was not likely due to a difference in physical effort as there was no difference in max HR reached in the single-task climb (M = 141.5 bpm, SD = 16.84) compared to the dual-task climb (M = 142.5 bpm, SD = 18.54), $t(11) = .399$, $p = .697$.

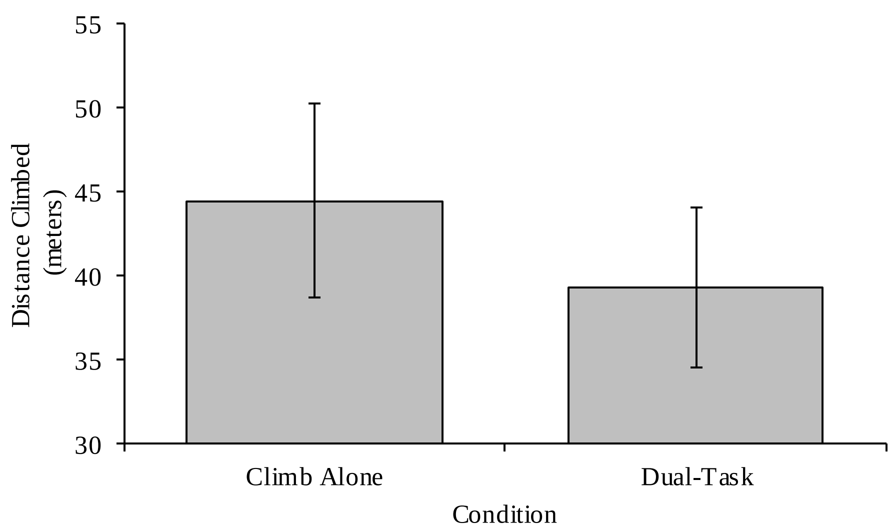

Figure 7-1. Average distance traversed in the single- versus dual-task conditions. Error bars are standard error of the mean.

Participants used significantly more holds per meter, indicating reduced climbing efficiency, in the dual- (M = 5.59, SD = 1.14) compared to single-task (M = 4.78, SD = 1.15) condition, $t(11) = 5.35$, $p < .001$, $M_{\text{difference}} = .81$ (95% CI [.48,1.14]), Cohen's $d_z = 1.544$ (95% CI [.849,2.239]), as shown in Figure 7-2.

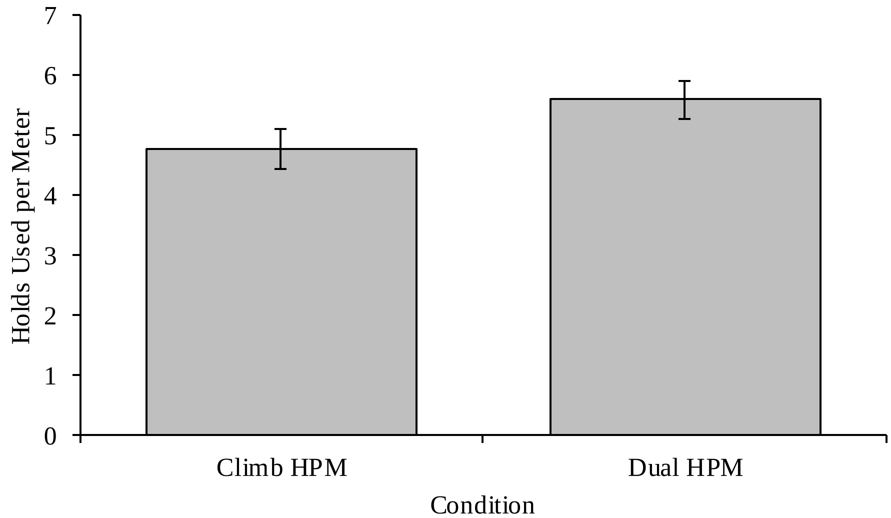

Figure 7-2. Average number of holds per meter used in the single- versus dual-task conditions. Error bars are standard error of the mean.

7.4.3 Subjective Stress State

The average ratings on the self-report scale are shown in Table 7-2. An analysis of variance showed significant within-subject effects of task on workload, $F(2,22) = 7.56$, $p = .003$, $\eta_p^2 = .407$, and on the spent component, $F(2,22) = 3.47$, $p = .049$, $\eta_p^2 = .240$ but no significant within-subject effects of task on task focus, $F(2,22) = .91$, $p = .417$, $\eta_p^2 = .076$. The sphericity assumption was not violated.

Table 7-2. Self report averages

	SA Alone	Dual-Task	Climbing Alone
Mental Demand	59.6(7.6)	73.3(7.5)	49.6(6.4)
Physical Demand	1.3(0.7)	61.3(6.7)	68.8(5.4)
Temporal Demand	19.2(6.4)	55.0(8.0)	41.7(9.1)
Emotional Demand	22.1(6.9)	27.9(5.6)	13.3(4.0)
Performance Monitoring Demand	37.1(7.3)	52.5(7.3)	46.3(8.4)
Effort	50.0(8.3)	68.3(6.9)	58.8(7.0)
Physical Fatigue	3.8(1.6)	42.9(7.9)	65.0(5.1)
Mental Fatigue	33.8(7.8)	53.3(7.5)	26.3(6.9)
Tense	25.0(8.7)	37.5(8.1)	22.1(6.4)
Unhappy	15.8(6.4)	16.7(7.1)	8.3(3.2)
Motivation	74.2(5.9)	79.6(4.7)	78.3(4.0)
Task Interest	55.8(6.7)	75.8(5.9)	71.3(7.4)
Self Related Thoughts	17.9(5.9)	23.3(7.3)	25.0(6.4)
Concentration	82.1(4.2)	82.5(6.1)	74.6(6.2)
Confidence	61.3(4.9)	56.3(7.3)	70.0(4.8)
Task Related Thoughts	74.6(7.7)	77.5(5.0)	69.6(7.4)
Task Unrelated Thoughts	14.2(4.2)	15.0(4.6)	18.3(6.4)
Workload	31.5(4.9)	56.4(5.1)	46.4(4.5)
Spent	23.4(4.6)	38.8(5.3)	30.3(3.0)
Task-Focus	79.8(3.4)	80.3(3.2)	75.8(3.6)

Note. Each value is the mean (standard error of the mean) self-report rating on the subjective stress state questionnaire across all participants for that measure, on a scale of 0-100.

Because of interest in the difference between single- and dual-task performance, planned contrasts were conducted. Dual-task workload (M = 56.39, SD = 17.56) was significantly greater than SA-alone workload (M = 31.53, SD = 17.07), $t(11) = 3.97$, $p = .002$, $M_{\text{difference}} = 24.86$ (95% CI [11.07,38.65]). The climb-alone workload (M = 46.39, SD = 15.51) was greater than the SA-alone workload, approaching significance, $t(11) = 2.13$, $p = .056$, $M_{\text{difference}} = 14.86$ (95% CI [-.48,30.21]). The spent component was significantly greater in the dual-task (M = 38.83, SD = 18.22) than the SA-alone task (M = 23.42, SD = 15.84), $t(11) = 2.91$, $p = .014$.

7.5 Discussion

Both tasks (SA and climbing) displayed dual-task costs relative to performing the tasks alone. Participants displayed statistically significantly greater SA in the seated task than the dual-task, and participants on average climbed with greater efficiency when unencumbered by the SA task. These results are consistent with the hypotheses that participants would perform better on both tasks when performed alone rather than concurrently and they are consistent with previous dual-task research involving climbing (Green et al., 2014). The difference in distance climbed failed to reach statistical significance, which is also consistent with some previous research (Darling & Helton, 2014; Green & Helton, 2011).

Participant's SA, indicated by A′, declined when performing a concurrent climbing task. As predicted, climbing was not only physically strenuous, but particularly demanding of cognitive resources. Climbing requires general executive resources to maintain attention, actively plan a route, and constantly monitor body orientation, and may also require not only spatial but verbal resources (Wickens, 2008), making it particularly interfering with the verbal SA task. A strong link exists between language and gesture, both neuro-anatomically and in practice, so perhaps the use of climbers' hands and arms impairs their ability to adequately process the verbal demands of the SA task (Frick-Horbury & Guttentag, 1998; Wagner, Nusbaum, & Goldin-Meadow, 2004; Xu, Gannon, Emmorey, Smith, & Braun, 2009). In addition, climbers may actually plan their route using an internal verbal monologue, even if the climbing itself is a spatial activity.

The participants in this experiment were experienced recreational and competitive climbers. One participant noted that the dual-task condition is different to competitive climbing such as soloing (climbing on one's own, without a belayer) and hard red-pointing (free-climbing a route that has not been planned out in advance) as these activities require blocking out all other sensory inputs to focus on the task at hand. This participant found it hard to switch mindsets for the experimental task. If other participants operated with this mindset as well, though dual-task deficits did occur in the climb, perhaps the decline in performance on the SA task was still partially due to task shedding. Remaining aware of potential situation hazards is clearly an important feature in recreational climbing, but this SA task may not be very realistic for that domain. However, because the climbing task has its own considerable SA demands, unlike the running and discrimination tasks, this too could have contributed to the decline in SA during the dual-task. Even though SA cannot be pinpointed specifically on the Multiple Resource Model, being required to complete essentially two SA tasks at once would intuitively cause greater interference than performing the SA task with a more dissimilar task. Future research should aim to use trained professionals, who understand the importance of both the physical task and remaining attentive to communication about the situation, as participants.

The prediction that participants would not climb as far or as efficiently in the dual-task condition, similar to Green and colleagues' research (Green et al., 2014), was only partially supported by the results. A clear difference in climbing efficiency (number of holds used per meter) in the single- compared to dual- task implies that performing the SA task utilizes cognitive resources that might otherwise be put towards planning the most efficient route across the wall. Though there is some evidence that people naturally prioritize physical demands (Darling & Helton, 2014; Epling, Blakely, et al., 2016; Green & Helton, 2011), particularly when injury is a real possibility, participants did succumb to the dual-tasking deficits in climbing element of this experiment, in addition to the SA element. Anecdotally, some participants admitted to focusing on the climbing element of the dual-task more than they focused on the SA scenario, yet the climbing deficits still occurred. Perhaps an increased number of holds used/decreased climbing efficiency is actually an indication of less risk taking. In addition, participants found listening to the actual scenario less distracting than the nonsensical scenario used for control in the climb-alone task. However, performance results suggest that, though listening to a story was "easier" than listening to noise, the listening may have been more passive than it was in the SA-alone task.

As expected, workload, task focus, and being "spent" tended to be greater in the dual-task than single-tasks as reported on the subjective questionnaire. Workload, as expected, was significantly greater in the dual-task than the SA task. No significant difference in task focus was found among the three different conditions, implying that both single tasks were engaging and demanding enough to require a great deal of focus, but performing them at the same time did not elicit "extra" focus. Participants were, however, more "spent" in the dual-task than the seated SA task.

As seen in Figure 7-3, the single-task SA performance (A´) remained relatively consistent across the different groups involved in this plus the two prior experiments. This demonstrates the reliability and usefulness of the new task. In addition, SA performance clearly declined in all three dual-task conditions. Climbing seems to be the most disruptive to listening to and remembering the SA scenarios, followed by the semantic discrimination task. Least disruptive was the running task. This trend in the level of disruption between tasks is consistent with prior research that used a word recall task in place of the SA task (Chapter 3; Epling, Blakely, et al., 2016). Even though the SA task requires narrative or episodic memory, the relative disruption is similar to that caused by the requirement to remember the list of words.

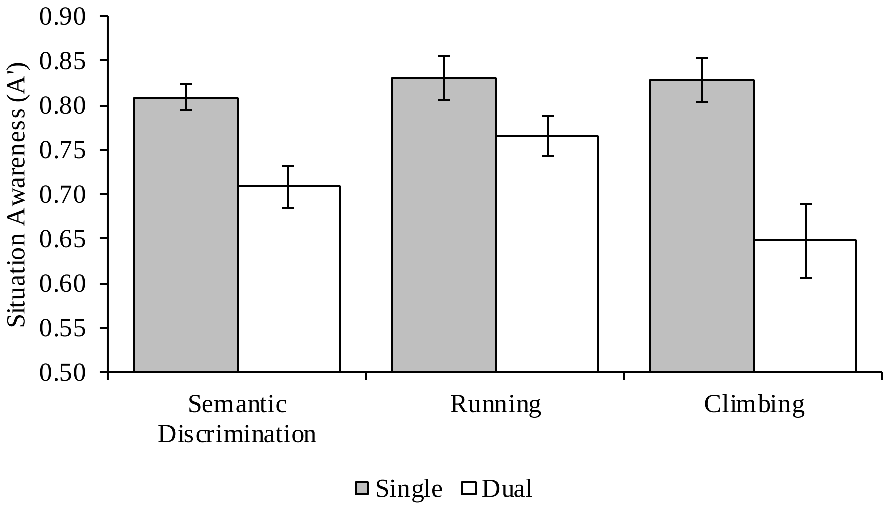

Figure 7-3. Effects of dual-task on SA A´ across experiments. Error bars are standard error of the mean.

The relative difference in SA performance can also be visualized using the standardized effect size (Cohen's d_z), as shown in Figure 7-4. According to conventional benchmarks (Nakagawa & Cuthill, 2007), the dual-task performance decline is considered a large effect in each of the three experiments. The standardized effect size was also calculated for the difference in performance between the single- and dual-task in the discrimination, running, and climbing tasks. In other words, it was important not only how much these tasks interfered with the SA task, but also how much the SA task caused a performance decline in these tasks. As seen in Figure 7-4, the relative degree of dual-task interference is similar when looking in the opposite causal direction: attempting to maintain SA harms climbing efficiency the most, followed by the percentage of hits achieved in the discrimination task, and lastly running distance.

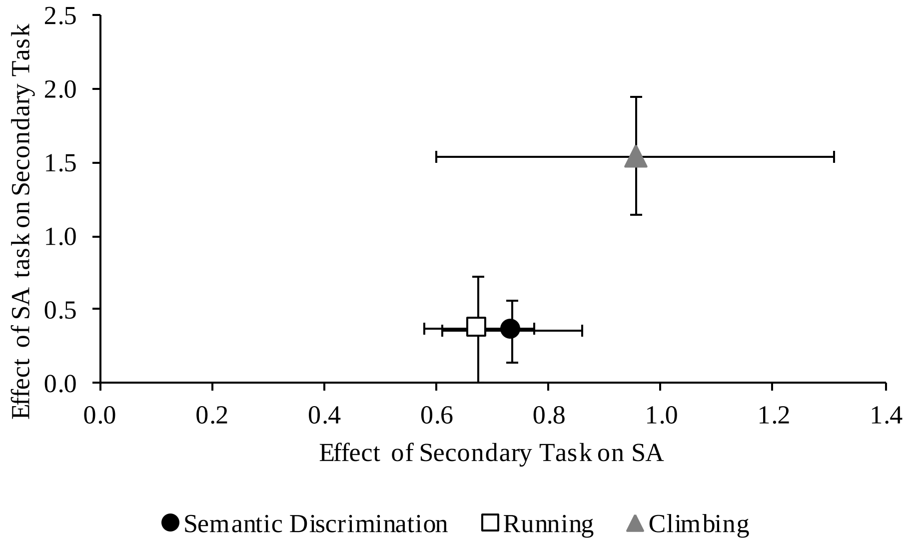

Figure 7-4. Effect sizes (Cohen's d_z) of dual-tasking interference. Error bars are standard error. The performance metric for the semantic discrimination task is proportion of hits, running is distance (m), climbing is efficiency.

Though no significant differences in bias were found between single- and dual-tasks, bias became more positive in all dual- compared to respective single-tasks, shown in Figure 7-5. This is consistent with prior research, and seems to indicate that when participants are trying to manage greater workload, bias becomes more strict/positive (Catherwood, Sallis, Edgar, & Medley, 2011). Using a narrower scope to evaluate the information is indicative of a more cautious approach and being less willing to accept information as true, which could lead to overlooking or rejecting important information about a situation.

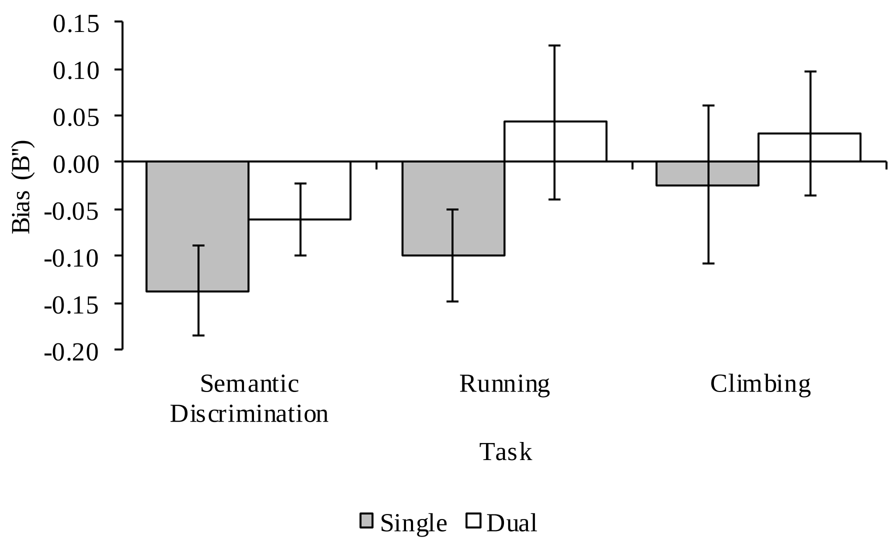

Figure 7-5. Effects of dual-task on situation awareness B´´ across experiments. Error bars are standard error.

Subjective stress state ratings in the running and climbing tasks were consistent with performance results. Subjective task focus while climbing is greater than that while running (Figure 7-6), which corroborates the idea that climbing takes an overall greater amount of cognitive resources than running.

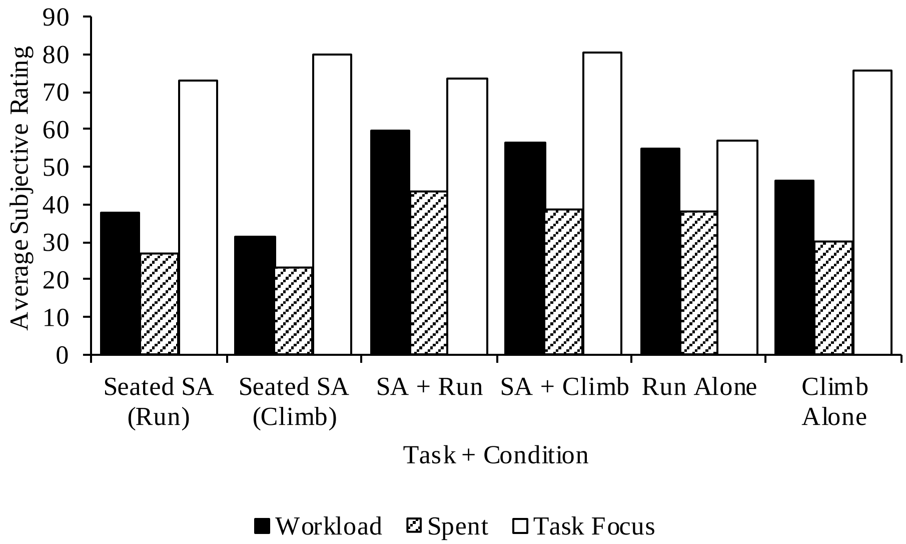

Figure 7-6. Subjective stress state questionnaire calculations.

In general, the results of the three experiments described above are consistent with past dual-tasking research, and provide support for the MRT. The SA task is verbal in nature, and because the discrimination task requires more domain-specific competing resources than the running task, interference is much greater than with the running task (Wickens, 2002, 2008). The sizable decline in SA while climbing indicates that climbing may require more global or executive resources, which may lend support to a unitary cognitive resource perspective. However, three other multiple resource-consistent explanations exist. First, there is a strong link between language and gesture, exhibited both in everyday life as well as in neuro-anatomical research (Frick-Horbury & Guttentag, 1998; Wagner et al., 2004; Xu et al., 2009). Because climbers' hands and arms are occupied, their ability to adequately process the outside verbal demands of the memory task may be impaired. Alternatively, though climbing is an activity that is spatial in nature, the traverse may actually be planned using verbal resources (i.e., an internal monologue). Finally, climbing itself requires SA on its own, possibly interfering with the independent SA task, as climbers must remain aware of the path they are navigating and the physical orientation and placement of body parts. These suggestions indicate that a dual-tasking performance decline between climbing and SA may be due to an overlap in processing code (verbal resource heavy) on Wickens' (2002, 2008) proposed matrix, on top of the executive resource demand of each. An alternative explanation is that the SA task actually requires more spatial resources than evident on the surface, due to an attempt to visualize what is happening in the scene in order to better retain the information. Perhaps there is resource demand interference in both the verbal and spatial dimensions. Regardless of specific demands of SA, the fact that climbers essentially are attempting to remain aware of two independent situations makes it relatively unsurprising but all the more important that such significant dual-tasking performance impairment was found.

In summary, semantic discrimination, running, and climbing are all shown to be cognitively demanding, as demonstrated in a decline in SA when performed in dual-task conditions, but to varying degrees. Because the amount of interference is different among each task pair, this indicates that the types of resources used are important factors in predicting the amount of dual-task interference and performance decline, and also suggests that such interference could be mitigated if the stage of processing, sensory channel, and processing code of paired tasks were planned with better neuroergonomic insight. This research adds to a growing matrix of dual-task pairings, helping to better understand the effects of dual-tasking when tasks do or do not overlap in their underlying cognitive resources. In the future, inserting different tasks into this dual-task paradigm will help achieve a better understanding of the cognitive resource structure, particularly in order to help with the safety and efficiency of physically and cognitively demanding tasks in high risk professions.

8 Interference between a Puzzle Task and Situation Awareness

8.1 Abstract

People can find it difficult to handle multiple tasks at once, though researchers have found evidence that it is easier to manage some task pairings than others. The Multiple Resource Theory (MRT) suggests that people have a set of specific, limited cognitive resources. If two tasks require the same resources (e.g., verbal – verbal), resources will be depleted faster and performance will decline more than if the two tasks required different resources (e.g., verbal – spatial). In the present research, an audio-verbal situation awareness (SA) task was performed concurrently with a visual-spatial puzzle task. Due to a non-overlap in specific resource requirements, minimal interference was expected. However, SA task performance declined when concurrently performed with the puzzle task. This result is consistent with the MRT when focusing on the overarching executive resource demand rather than specific task demands, as the puzzle task requires planning. The employment of the SA task in a new dual-task scenario sheds more light on the human cognitive resource structure to help predict where dual-task performance impairments may occur in real-world settings.

8.2 Introduction

A better understanding of the true cognitive resource structure is important for predicting and preventing performance breakdowns in a variety of settings. Many high risk procedures, including firefighting, military missions, search and rescue, medical operations, and piloting aircraft or automobiles, can involve attending to a variety of demands at once (Green & Helton, 2011; Helton et al., 2013). For example, search and rescue operators must actively navigate treacherous terrain, use maps or GPS devices, and remain in constant contact with an intelligence source. Such an operation clearly requires exceptional mental and physical aptitude, but is it actually possible to attend to everything at once, without aid? In the name of cost effectiveness, attempting to get more done with fewer people is common, but overloading individuals could set them up for failure. Knowing what cognitive resources are necessary to perform certain tasks can better inform how the tasks should be presented (e.g., audio versus text communication), which task pairs can truly be managed at the same time, and when offloading, automation, or human assistance is essential.

Though people are not often perfectly adept at multi-tasking, some research suggests that people can more easily perform certain task pairings than others. In contrast to Kahneman's (1973) central capacity theory of attention, Wickens suggested that the human cognitive resource structure can be broken down into four specific dimensions, each with discrete levels. This Multiple Resource Model (Wickens, 2002, 2008) can be used to predict where the most severe breakdowns in dual-tasking performance will occur, based on more than just the "amount" of resources required. Given equal task difficulty and overall resource demand, two tasks would interfere more if they demanded the same level (or type) of resources on any of the dimensions (Wickens, 2002, 2008). The first dimension is processing stage, with tasks requiring either perception/cognition or responding. The second dimension is perceptual modality, which can be either auditory or visual. The third dimension is visual channel (for certain tasks), which can be either focal or ambient vision. The final dimension is processing code, which is either spatial or symbolic/verbal. Wickens suggested that this 4D model can be used to predict the performance on two time-shared tasks, but he recognized the inherent "cost of concurrence" or executive demand present in any time sharing and division of attention, regardless of individual task demands (Navon & Gopher, 1979; Wickens, 2002). Wickens created a conflict matrix allowing one to predict the relative interference of two tasks given their resource demand plus an assumed baseline conflict value (Wickens, 2002).

Though the Multiple Resource Theory (MRT) has gained support through the years, further systematic testing and validation are important. In addition, when the resources required by specific tasks are not readily apparent, the model is somewhat unhelpful. The purpose of the present research was to use a situation awareness (SA) task in a new dual-task scenario in order to better understand the resource requirements of each task and whether the level of dual-task interference supports the MRT. By comparing performance on each individual task to simultaneous task performance (within-subjects design), the relative performance change, i.e., dual-task cost of a given pairing, becomes evident. By holding one task (i.e., the SA task) constant across a variety of secondary tasks, the dual-task cost across various pairings can be compared to infer specific resource requirements relative to other tasks.

In the present research, participants performed a visual-spatial puzzle and SA dual-task. Maintaining SA is a ubiquitous requirement in many military, firefighting, and search and rescue operations, but it has not often been researched as an independent task in a dual-task scenario. SA is formally defined as the perception, processing, and projection of important environmental information (Endsley & Garland, 2000), and thus likely requires a variety of cognitive resources. Because maintaining quality SA is crucial to good decision making and overall mission success, it is important to better understand the true demand it imposes on operators, and how maintaining SA may interfere with secondary task elements. Finally, the SA task was chosen to replace a verbal recall task previously employed in similar task pairings. The SA task is a more ecologically relevant task, and requires narrative recognition memory opposed to verbatim recall, which may cause less overall interference when dual-tasking. The SA task used in Chapters 5-7 is used again in the present research. In this task, the narrated SA scenario is presented to the participants before they take a true/false memory assessment, therefore requiring audio and verbal processing. The SA task may require other resources as well; for example, visualization of the scene as a memory technique may tap into spatial resources rather than relying on verbal memory of the story.

The puzzle task Quadra is an open source version of the common computer game Tetris. The Quadra task was chosen to pair with the SA task because it is simple to learn, fun for participants, and taps into both visual-spatial and planning (executive) resources, but does not require the verbal or auditory resources needed for the SA task (Haier et al. 2009; Strang et al. 2011; Strang et al. 2013; Strang et al. 2014). Haier and colleagues found MRI evidence that successful gameplay requires visual, spatial, and tactile resources, but they suggested that the game does not necessarily require episodic memory (Haier et al., 2009). The Quadra game has been shown to impair a verbal free recall memory task (Epling, Blakely, Russell, & Helton, 2017), but it is unknown whether it will be as detrimental to the more naturalistic narrative memory requirement (though still audio-verbal) of the SA task. By repeating not only the SA task with a variety of secondary tasks, but also repeating the Quadra task paired with a different primary task, this research will further add to the growing network of research exploring the cognitive resource matrix. The hope is to better understand why different relative amounts of interference occur even when task demands seem similar. Dual-task research has been criticized for failing to first objectively asses the resources required in each task (Navon, 1984), but continuing to build upon the array of dual-task pairings make the requirements of each task increasingly transparent. The present research presents the fourth pairing using this particular SA task (see Chapters 5-7), and the second pairing using the Quadra task (see Chapter 4).

The present research involved two single-task conditions (Quadra and SA) and a dual-task condition where participants performed both tasks at once. The SA task required participants to listen to an audio scenario that would later be assessed in a true/false memory test. In Quadra, participants manipulated falling puzzle pieces (tetrominoes) in order to complete horizontal rows, without gaps. Wickens (2002) suggested that any task pairing will result in moderate performance decline on both tasks. However, considering the minimal overlap in the present tasks' resource requirements on the MRT dimensions (though the SA task may require some spatial thinking), the dual-task decline should be minimal, with any interference likely being due to demand on the central executive (Wickens, 2008). Although resources did not seem to overlap between a Quadra and verbal recall task, it was recently found that playing the game significantly impaired recall. The planning component was a likely explanation for that decline. Additionally, the recall task did not significantly impair Quadra performance, for unknown reasons (Chapter 4; Epling, Blakely, Russell, et al., 2017). Therefore, in this research it was predicted that Quadra performance would not decline in the dual- compared to single-task condition, but it *was* expected that Quadra would impair SA task performance. Participants were also required to report subjective workload after each individual or dual-task, and it was expected that the dual-task would impose greater subjective workload than either task individually.

8.3 Method

8.3.1 Participants

Fifty undergraduate psychology students (44 females) at the University of Canterbury served as participants for course credit. All participants had normal or corrected-to-normal vision, normal hearing, and were fluent English speakers based on self-report. Age of participants ranged from 17 to 46 years (M = 19 years, SD = 4.11). The experimented was conducted under conditions approved by the University Human Ethics Committee, and informed consent was gained from each participant.

8.3.2 Materials

8.3.2.1 Situation Awareness Task

See Chapter 5 for details.

8.3.2.2 Quadra Task

See Chapter 4 for details.

8.3.2.3 *Dual-Task*

The five minute game of Quadra was run simultaneously with the second audio scenario.

8.3.2.4 *Questionnaire*

The NASA-TLX was used to collect participants' subjective workload in each task (see Appendix C and Chapter 2 for details).

8.3.3 Procedure

Participants were tested individually or in separated pairs at computer workstations in a laboratory at the University of Canterbury. Participants were unrestrained and seated approximately 50cm from eye-level screens (377 x 303 mm, 60 Hz refresh rate). Participants were asked to put on the headphones and adjust computer loudness to a comfortable level before beginning.

Participants were verbally instructed how to complete each task and were given the opportunity to ask questions. Participants were told that when playing Quadra, the objective was to achieve the highest score possible by fitting together the falling tetrominoes into horizontal rows without gaps. When a row was completed, that row would be cleared. They were told how to use the arrows and space bar to control the falling tetrominoes, and shown the screen location where the next tetromino could be seen. Participants were told that when listening to the audio scenarios, the objective was to remember as much as possible, as they would later be given a true/false assessment about the scenario. Participants were shown the response grid (Figure 5-1) and instructed how to fill out their true/false responses and confidence ratings. In addition to these two single-tasks, participants were told that they would also be completing a dual-task, for which the objective was to do their best on both tasks at the same time.

Participants were given a two minute practice session on the Quadra game, and then asked if they had any additional questions. The experimental tasks were then begun. This experiment was a within-subjects design, and participants were randomly assigned to one of six groups representing the orders of the three tasks. The two audio scenarios were randomly paired with either the dual-task or the SA-alone condition. The researcher manually started each task on the computer. For the SA task-alone condition, participants listened to the five minute audio track. Computer screens remained blank and participants were reminded to remember the scenario to the best of their ability. When the audio track finished, participants were instructed to carefully fill out the response grid. For the Quadra-only condition, participants were reminded to achieve the highest score possible in the given time. During this condition, participants heard the scrambled SA scenario and were told there was no memory imperative. For the dual-task condition, participants performed a five minute game of Quadra, while listening to the other audio track (depending on their group in the counterbalance). They were told to do their best on both tasks. At end of this condition, participants were instructed to carefully fill out the true/false response grid. Upon completing of each of the three conditions, participants filled out the NASA-TLX before advancing to the next part.

8.4 Results

8.4.1 Situation Awareness

Each SA true/false test had 24 probes. One scenario has 10 true and 14 false probes, and the other had 12 true and 12 false. In addition to marking each probe as true or false, participants were asked to rank their confidence on each response as a guess, fairly uncertain, fairly certain, or certain (scored 1-4 respectively). For each participant the number of overall correct responses was scored, and the proportion of hits (true statements marked as true) and false alarms (false statements marked as true) were calculated for the single- and dual-task. The signal detection theory metrics of A´ (sensitivity) and B´´ (bias) were then calculated using the technique described by Edgar and colleagues (Edgar et al., 2003). The average confidence for each participant in each task was also calculated as a measure of perceived SA.

Participants responded correctly to significantly more probes in the single- (M = 17.8, SD = 2.76) compared to dual-task (M = 15.5, SD = 2.44) condition, $t(49)$= 5.19, p < .001, $M_{\text{difference}}$ = 2.30 (95% CI [1.41,3.19]). For correct detections, participants made a significantly greater proportion of hits in the single- (M = .812, SD = .127) compared to the dual-task condition (M = .749, SD = .132), $t(49)$ = 2.77, p = .008, $M_{\text{difference}}$ = .063 (95% CI [.017,.109]). Participants also made a significantly lower proportion of false alarms in the single- (M = .314, SD = .175) compared to the dual-task condition (M = .441, SD = .127), $t(49)$ = 4.78, p < .001, $M_{\text{difference}}$ = .127 (95% CI [.074,.180]).

For A´, participants had significantly higher sensitivity to true probes in the single-task (M = .823, SD = .119) than the dual-task (M = .742, SD = .129), $t(49)$ = 4.48, p < .001, $M_{\text{difference}}$ = .099 (95% CI [.054,.143]), Cohen's d_z = .634 (SE = .189). For B´´, participants showed no significant difference in bias in responding between the single- (M = -.152, SD = .306) and dual-task (M = -.175, SD = .192) conditions, $t(49)$ = .49, p = .622, $M_{\text{difference}}$ = .024 (95% CI [-.072,.119]).

Participants were significantly less confident about their responses (lower perceived SA) in the dual- (M = 2.79, SD = .358) compared to single-task (M = 3.17, SD = .369), $t(49)$ = 6.71, p < .001, $M_{\text{difference}}$ = .383 (95% CI [.268,.498]).

8.4.2 Quadra

A paired samples t-test revealed no significant difference between participants' Quadra scores in the single-task (M = 5898, SD = 3600) and dual-task (M = 5988, SD = 3545) conditions, $t(49)$ = .226, p = .822, $M_{\text{difference}}$ = 90.1 (95% CI [-709.5, 889.7], Cohen's d_z = .032 (SE = .111). There was also no significant difference in Quadra score when comparing participants' first game (either the single- or dual-task based on the counterbalance; $M = 5722$, $SD = 3253$) to second game ($M = 6164$, $SD = 3854$) of Quadra, $t(49) = 1.125$, $p = .266$, $M_{\text{difference}} =$ (95% CI [-347.8, 1232.0]).

The number of wells required in each condition (if a well filled to the top, a clear well was provided) was explored as a measure of assistance needed in each condition. Twenty-six of the participants required the well to be cleared at least one time in at least one of the two Quadra conditions. Among these, there was no significant difference in the number of wells used in the single- ($M = 1.85$, $SD = .464$) and the dual-task ($M = 1.65$, $SD = .745$) condition, $t(25) = 1.044$, $p = .306$, $M_{\text{difference}} = .192$ (95% CI [-.187,.572].

Significantly more tetrominoes were played in the single- ($M = 73.8$, $SD = 19.5$) compared to dual-task condition ($M = 69.9$, $SD = 19.7$), $t(49) = 2.50$, $p = .016$, $M_{\text{difference}} = 3.88$ (95% CI [.75,7.01]). However, there was no significant difference in efficiency of gameplay between the single- ($M = 76.8$, $SD = 37.1$) and dual-task ($M = 84.1$, $SD = 40.5$) conditions (the number of points earned in that condition divided by the number of tetrominoes played), $t(49) = 1.36$, $p = .179$, $M_{\text{difference}} = 7.27$ (95% CI [-3.45,17.98]).

8.4.3 Subjective Workload

The average ratings on each subscale of the NASA-TLX are shown in Table 8-1. The average workload component is the mean of the six subscales. Planned comparisons revealed that dual-task workload ($M = 46.00$, $SD = 16.18$) was greater than Tetris-alone workload ($M = 40.13$, $SD = 15.53$), $t(49) = 2.86$, $p = .006$, $M_{\text{difference}} = 5.67$ (95% CI [1.74,9.99]) and SA-alone workload ($M = 30.68$, $SD = 11.33$), $t(49) = 8.09$, $p < .001$, $M_{\text{difference}} = 15.32$ (95% CI [11.51,19.12]). The Tetris-alone workload was significantly greater than the SA-alone workload $t(49) = 4.45$, $p < .001$, $M_{\text{difference}} = 9.45$ (95% CI [5.19,13.72]).

Table 8-1. Self-report average on the TLX subscales

	SA	Dual-Task	Tetris
Mental Demand	42.2(3.1)	61.1(3.3)	46.3(3.3)
Physical Demand	8.2(1.7)	16.9(2.8)	14.4(2.2)
Temporal Demand	24.9(2.4)	43.4(3.6)	44.4(3.3)
Performance	38.2(2.4)	52.3(2.7)	41.9(3.2)
Effort	49.0(3.0)	62.3(3.1)	52.0(3.1)
Frustration	21.6(2.7)	40.0(3.6)	41.8(3.6)
Average	30.7(1.6)	46.0(2.3)	40.1(2.2)

Note. Each value is the mean (standard error of the mean) self-report rating across all participants for that measure, on a scale of 0-100. The average workload rating is the mean of the six subscales.

8.5 Discussion

Participants were able to maintain better SA when that was their only objective, as every performance metric indicated a decline in SA in the dual-task. Participants had fewer accurate responses overall on the SA true/false test, and also made fewer hits, more false alarms, had lower sensitivity to true probes, and had lower perceived SA in the dual- compared to single-task. Though bias did not differ between tasks, previous research has shown that people tend to be relatively stable in their response strategies (Catherwood et al., 2012, 2011; Edgar et al., 2003; Sallis et al., 2013). The overall effect size, Cohen's d_z = .634, shows a moderate interference effect of Quadra on SA. Consistent with previous research and hypotheses, performing the SA task did not seem to impair performance on the Quadra task; none of the Quadra performance metrics revealed significant differences. The effect size of performance impairment of the SA task on the Quadra score was negligible, Cohen's d_z = .032. The effect size dual-task performance decline in the Quadra-SA pair can be seen in relation to the prior experiments using the same SA task in Figure 8-1 below.

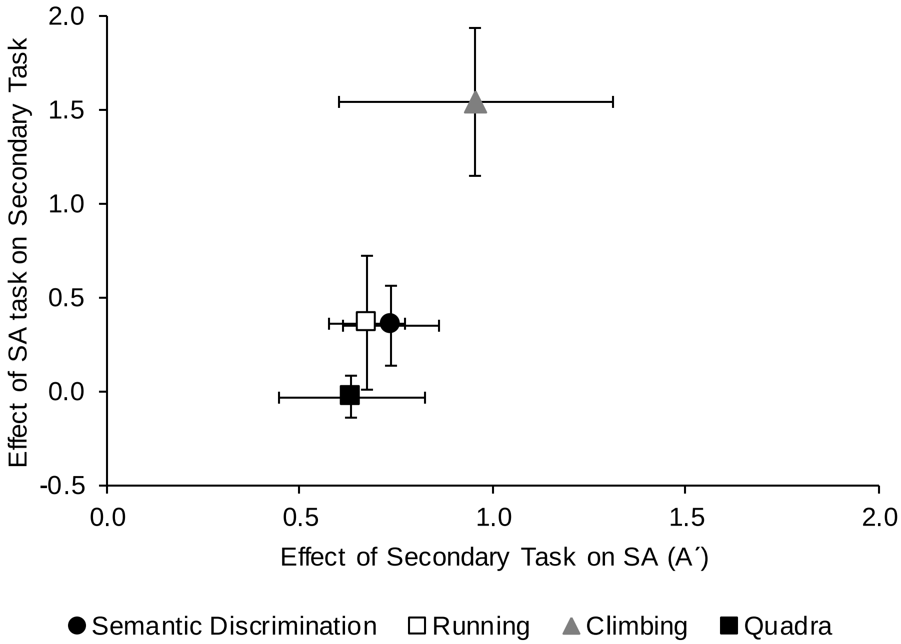

Figure 8-1. Standardized effect sizes (Cohen's d_z) for interference effect of different experimental tasks on SA (x-axis) and the interference effect of the SA task on those same experimental tasks (y-axis). The performance metric for the semantic discrimination task is proportion of hits, running is distance (meters), climbing is efficiency (holds per meter), and Quadra is raw game score. Error bars are standard error of the mean for their respective dimensions.

Several possible reasons could explain why SA performance was worse in the dual-task. First, Wickens suggested that any dual-task pairing, regardless of specific task demands, will result in some baseline amount of interference (Wickens, 2002). Secondly, the executive demand – planning where the current and future tetrominoes will fit into the well to complete rows in the most efficient and speedy manner possible – imposes an additional demand on the general resource pool. Wickens recognized the importance of the central executive in understanding multi-tasking performance (Wickens, 2008), though it is not clearly accounted for in his model. The planning required by the Quadra task could be causing a central executive bottleneck, not allowing the lower level task-specific resources to be utilized efficiently.

Finally, it is entirely possible that the SA scenarios, though delivered via audio modality and verbal code, are processed visually and spatially. The audio scenarios were developed from visual equivalents for ease of delivery and dual-tasking ability; the scenario easily allows participants to visualize what is happening and spatially process where events are occurring. This would therefore cause specific resource interference with the Quadra task, at least partially, which also utilizes the visual perceptual modality and spatial processing code. Though it cannot be proven whether a general bottleneck or specific resource overlap is the true cause of interference, these results add weight to argument that even the resource requirements of simple tasks are not necessarily as obvious as they seem.

Though SA performance declined in the dual-task, no decline was detected for Quadra performance. An extremely large range of Quadra scores could be partially to blame for the lack of noticeable dual-task effects. As mentioned in Chapter 4, a longer practice period should be given to minimize any practice effects, increase overall performance, and hopefully reduce the large variance between participants. Unfortunately, this research was conducted at the same time as the aforementioned study; therefore, it was too late to amend the protocol once the lesson was learned. Due to the large variation, a median split was performed on Quadra scores, and these analyses can be seen in Appendix F.

Because the overall performance score shed little light on potential differences between single- and dual-task conditions, the difference in scores between the first and second game of Quadra was also analyzed to look for significant practice effects. Because of the counterbalance, half of participants' first experimental game of Quadra was the single-task, and half was the dual-task. Because the practice session was only two minutes, perhaps participants' improvement from first to second game overshadowed potential differences in single- and dual-task. However, no significant difference was found between first and second games. It is plausible that the practice effect and dual-task effect cancelled each other out. In addition, the number of wells cleared was computed as a measure of assistance required. If no difference in score occurred between the single- and dual- task, perhaps it was because participants utilized more assistance in the dual-task. Intentional attainment of a new well, given the settings of this particular game, would be a very strategic move: it is easier to plan ways to clear rows when there is more space within the well because there is thus more time to work with. Since there was no penalty for filling a well to the top, if a player filled the well beyond halfway it would behoove the player to hold down the spacebar to rapidly drop pieces to fill the present well quickly and start fresh with a new well. However, few participants utilized extra wells, and this seemed to be more a function of overall gameplay ability (the higher scoring players generally didn't use extra wells) rather than the utilization of assistance in the more difficult condition. Future research should probe for participants' individual strategies and perhaps constrain or suggest specific strategies. For example, a score penalty for using multiple wells could be imposed to discourage that strategy, or conversely, the strategy could be actively suggested. Finally, it is impossible to prove that participants allocated resources to both tasks in a balanced way. Perhaps engagement in the Quadra task led participants to consider this their primary objective, therefore leading to dual-task performance decline only in the perceived "secondary" task.

9 Interference between a Sustained Attention to Response Task and Situation Awareness

9.1 Abstract

People are quite poor at handling multiple tasks at once, though researchers have found evidence that it is easier to manage some task pairings than others. The Multiple Resource Theory (MRT) suggests that people have a set of specific, limited cognitive resources. If two tasks require the same resources (e.g., verbal – verbal), resources will be depleted faster and performance will decline more than if the two tasks required different resources (e.g., verbal – spatial). In the present research, an audio-verbal situation awareness (SA) task was performed concurrently with a visual-spatial Sustained Attention to Response Task (SART). Due to there being little overlap in specific resource requirements, minimal interference was expected. Neither SA task performance nor SART performance declined when concurrently performing the two tasks compared to performing them individually. This result is consistent with the MRT. Continuing to use the SA task in new dual-task scenarios sheds more light on the human cognitive resource structure which can eventually help to better predict where dual-task performance impairments may occur in real-world settings.

9.2 Introduction

This chapter explores a sustained attention to response task (SART) paired with the situation awareness (SA) task (Chapters 5-8), and was originally prepared for publication in conjunction with Chapter 8 as a two-experiment article. In this thesis, care has been taken to separate and explain the importance of each stand-alone experiment, so the entire introduction from Chapter 8 will not be repeated at this time. One can assume that all of the prior explanation on dual-tasking research, SA, and the MRT still apply, and readers are encouraged to look to prior chapters for more information.

In the present research, participants performed a response inhibition task paired with the situation awareness (SA) task (Chapters 5-8). The response inhibition task is a simple numerical version of the Sustained Attention to Response Task (SART). In SART, operators respond to frequently occurring "Go" stimuli and withhold a response from infrequent "No-Go" stimuli (Funke et al., 2012). SART tasks have been used as a response inhibition and executive control task (Head & Helton, 2013; Helton, 2009; Helton, Head, & Russell, 2011; Manly et al., 2004; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). Commission errors (failure to withhold a response from No-Go items) in SART result from the repetitive responding to frequent events (Wilson, Russell, & Helton, 2015). This is because frequent responding leads to a pre-potent ballistic motor response which becomes difficult to inhibit (Head & Helton, 2013, 2014a; Helton, Weil, Middlemiss, & Sawers, 2010; Wilson et al., 2015), particularly when operators are told to respond as quickly as possible (speed-accuracy trade-off; Helton 2009; Helton et al. 2009; Helton et al. 2011; Wilson et al. 2015).

Dual-tasking with SART was chosen for a variety of reasons. SART requires constant monitoring, responding, and inhibition of automatic impulses – posing both a physical and cognitive challenge - but does not require (or allow for) planning. The task requires visual-spatial resources to discern the digit and/or the location of the digit, but no word processing or auditory resources like the SA task. In addition, the SART task requires different resources than the semantic discrimination, running, and climbing tasks the SA task has already been paired with (Chapters 5-7), and does not require the planning component of the visual-spatial Quadra task (Chapter 8). Finally, due to the importance of response inhibition in a variety of critical roles, a better understanding of how an operationally relevant additional task (SA) may affect SART performance is important for preventing unfortunate consequences in real-world operations (Dillard et al., 2014).

This experiment involved two single-task conditions (SA alone and SART alone) and a dual-task condition where participants performed both the SA and SART tasks simultaneously. According to Wickens (2002), the mere act of dual-tasking will likely result in some performance decline compared to individual task performance. However, considering the lack of overlap in the present tasks' resource requirements on Wickens' dimensions, the dual-task decline should be minimal. Although resources did not seem to overlap between a Quadra and verbal recall task, it was recently found that playing the game significantly impaired both recall (Chapter 4; Epling, Blakely, Russell, et al., 2017) and SA (Chapter 8). The planning component was a likely explanation for that decline. The particular SART task employed here required participants to monitor visually salient digits appearing in consistent locations (with Go digits appearing in different location than No-Go digits) and respond to all numbers 0-9 except for 3. This SART task utilizes visual and spatial resources, but requires no planning. However, the task requires active inhibition of impulsive responding. Previous research found a performance decline in both the SART task and a word recall task in a dual-task pairing (Head & Helton, 2014b), so at least some performance impairment in the dual-task condition was expected. Thus, reduced SA was expected in the dual- compared to single-task condition, but to a lesser extent than that found in Chapter 8. Participants were also required to report subjective workload after each individual or dual-task, and the dual-task was expected to impose greater subjective workload than either task individually. Unlike most previous SART research, the current interest is primarily the difference between single- and dual-task performance, rather than performance trends over time.

9.3 Method

9.3.1 Participants

Thirty-five undergraduate psychology students (25 women) at the University of Canterbury served as participants for course credit. All participants had normal or corrected-to-normal vision, normal hearing, and were fluent in English speakers. Age of participants ranged from 18 to 52 years (*M* = 24 years, *SD* = 8.71). The study was approved by the University Human Ethics Committee, and informed consent was gained from each participant.

9.3.2 Materials

9.3.2.1 Situation Awareness Task

See Chapter 5 for details.

9.3.2.2 Sustained Attention to Response Task

The SART task used in this experiment presented the numbers 1 - 9 in one of three positions on the screen. The spacebar was used to respond to all Go items (all digits except 3), which always appeared in the center of the screen. The No-Go item (3) always appeared either to the right or left of center of the screen. All of the numbers were in black Courier New font and could appear in five different sizes ranging from 48 to 120. Audio and visual stimuli presentations and recordings of reaction times and accuracy were executed by PC computers with E-Prime Professional 2.0 (Schneider et al., 2002). Stimuli appeared for 250ms, followed by a 900ms mask, giving an inter-trial response period of 1150ms. The stimuli presentation were programmed in blocks of 51.75 seconds, each block randomly presenting 5 No Go and 40 Go stimuli (No-Go target probability was 1/9 and Go probability was 8/9). The program looped through 6 blocks for a total trial time of 5 minutes and 10 seconds. To control for any noise effects in the dual-task compared to SART-alone condition, a scrambled scenario was played during the latter. The scenario was incomprehensible and participants were told that there was no memory imperative.

9.3.2.3 Dual-Task

The SART task was used again in the dual-task, along with the alternate SA scenario. The SA scenario began playing 10 seconds after the SART task began, so that the time between the end of the recording and commencing the SA true/false test would be consistent in all conditions.

9.3.2.4 Questionnaire

The NASA-TLX was used to collect participants' subjective workload in each task (see Chapter 2 and Appendix C for details).

9.3.3 Procedure

Participants were tested in groups or individually at cubicle workstations in a computer laboratory at the University of Canterbury. Participants were unrestrained and seated approximately 50cm from eye-level screens (377 x 303 mm, 60 Hz refresh rate). Participants were asked to put on headphones and adjust computer loudness before beginning, and to put away cell phones and watches.

Participants were verbally instructed how to begin the experiment. Upon launching the program, participants were prompted to enter biographical data, and then progress through instructional slides. The computer program assigned them to a task order, and then displayed instructions for each task, which were also repeated at the commencement of each task. For the SA single-task, participants listened to the five minute audio track. Computer screens remained blank and participants were reminded to remember the scenario to the best of their ability. When the audio track finished, participants filled out the response grid. For the SART task, participants were instructed to monitor the screen and press the space bar in response to all numbers except for the number 3, and to respond as quickly and accurately as possible. Participants were told they could ignore the audio track that would play during this task. For the dual-task, participants performed another SART session, while also listening to the other SA scenario. At end of the task, participants were instructed to fill out the true/false response grid. Upon completing each task, participants were also instructed to fill out the NASA-TLX before advancing to the next task.

After reading the instructions, participants were given a SART practice session where they saw 16 stimuli and were given audio hit or miss feedback. If participants did not have addition questions, they advanced to the experimental tasks. This experiment was a within-subjects design, and participants were randomly assigned to one of six groups representing the orders of the three tasks. The two audio SA scenarios were randomly paired with either the dual-task or the SA alone condition.

9.4 Results

9.4.1 Situation Awareness

Each SA true/false test had 24 probes. One scenario had 12 true and 12 false probes, and the other scenario had 10 true and 14 false. Participants were also asked to rank each response as a guess, fairly uncertain, fairly certain, or certain (scored 1-4 respectively) showing their level of confidence on each probe and overall perceived SA. For each participant the number of correct probe responses (correct detections) was tallied, and the proportion of hits and false alarms for each task (single- and dual-task) was calculated. Then signal detection theory metrics of A´ (sensitivity) and B´´ (bias) were calculated from these proportions using the process described by Edgar and colleagues (2003). The average confidence of each participant in each task was calculated as a measure of perceived SA.

No significant difference was found in the number of correct responses in the SA task between the single- (M = 18.2, SD = 2.47) and dual-task (M = 17.4, SD = 2.85) conditions, $t(34)$= 1.539, p = .133, $M_{\text{difference}}$ = .800 (95% CI [-.256,1.856]. There was no significant difference in the proportion of hits between single- (M = .81, SD = .15) and dual-task (M = .80, SD = .15) conditions, $t(34)$ = .511, p = .612, $M_{\text{difference}}$ = .01 (95% CI [-.04,.06]. There was also no significant difference in the proportion of false alarms between single- (M = .28, SD = .13) and dual-task (M = .33, SD = .14) conditions, $t(34)$ = 1.461, p = .153, $M_{\text{difference}}$ = .05 (95% CI [-.02,.11]).

For A´, situation awareness (sensitivity to true probes) in the single-task (M = .834, SD = .104) was not significantly different to the dual-task condition (M = .799, SD = .145), $t(34)$ = 1.525, p = .136, $M_{\text{difference}}$ = .036 (95% CI [-.012,.083], Cohen's d_z = .258 (SE = .185). There was also no significant difference between tasks in B´´ between single- (M = -.174, SD = .291) and dual-tasks (M = -.189, SD = .249), $t(34)$ = .273, p = .787, $M_{\text{difference}}$ = .015 (95% CI [-.097,.127]. Participants were, however, significantly less confident about their responses (lower perceived SA) in the dual- (M = 2.89, SD = .469) compared to single-task (M = 3.06, SD = .450), $t(34)$ = 2.33, p = .026, $M_{\text{difference}}$ = .175 (95% CI [.022,.328]).

9.4.2 SART

The SART program included 6 blocks of stimuli presentation (each block with 40 Go and 5 No-Go stimuli). For each participant, the proportion of errors of omission (out of 240) and commission (out of 30) were calculated for the single- and dual-task.

There was no significant difference in proportion of errors of omission between the single- (M = .006, SD = .007) and dual-task condition (M = .007, SD = .012), $t(34)$ = .507, p = .616, $M_{\text{difference}}$ = .001

(95% CI [-.003,.005]). There was no significant difference in proportion of errors of commission between the single- (M = .151, SD = .068) and dual-task condition (M = .180, SD = .129), $t(34) = 1.612$, $p = .116$, $M_{\text{difference}}$ = .029 (95% CI [-.007,.065]). There was also no significant difference in the average reaction time of correct responses to Go stimuli between the single- (M = 308ms, SD = 39.9) and dual-task conditions (M = 316ms, SD = 38.6), $t(34) = 1.198$ $p = .239$, $M_{\text{difference}}$ = 7.89 (95% CI [-5.49,21.27]).

9.4.3 Subjective Workload

The average rating on each subscale of the NASA-TLX is shown in Table 9-1.

Table 9-1. Self-report average on the TLX subscales

	SA	Dual-Task	SART
Mental Demand	51.1(3.9)	74.9(2.3)	66.1(3.7)
Physical Demand	12.0(2.5)	25.1(3.8)	26.7(4.0)
Temporal Demand	39.6(4.0)	70.0(2.9)	67.6(3.5)
Performance	39.1(3.2)	43.4(2.7)	44.4(3.8)
Effort	53.4(3.7)	72.1(2.4)	66.4(3.4)
Frustration	32.9(4.2)	45.6(4.5)	57.0(5.2)
Average	38.0(2.5)	55.2(2.0)	54.7(2.8)

Note. Each value is the mean (standard error of the mean) self-report rating across all participants for that measure, on a scale of 0-100. The average workload rating is the mean of the six subscales.

Planned comparisons revealed that dual-task average workload (M = 55.19, SD = 11.61) was not significantly different than SART-alone workload (M = 54.71, SD = 16.31), $t(34) = .195$, $p = .846$, $M_{\text{difference}}$ = .48 (95% CI [-.4.48,5.43], but was significantly greater than SA-alone workload (M = 38.02, SD = 14.84), $t(34) = 7.958$, $p < .001$, $M_{\text{difference}}$ = 17.17 (95% CI [12.78,21.55]). The SART-alone workload was also significantly greater than the SA-alone workload $t(34) = 9.278$, $p < .001$, $M_{\text{difference}}$ = 16.69 (95% CI [13.03,20.35]).

The mental demand subscale was significantly higher in the dual-task condition (M = 74.9, SD = 13.4) than the SART-alone condition (M = 66.1, SD = 21.9), $t(34) = 2.53$, $p = .016$, $M_{\text{difference}}$ = 8.7 (95% CI [1.7,15.7]), though frustration was significantly higher in the SART-alone (M = 57.0, SD = 30.9) compared to dual-task condition (M = 45.6, SD = 30.9), $t(34) = 2.74$, $p = .010$, $M_{\text{difference}}$ = 11.4 (95% CI [2.9,19.9]).

9.5 Discussion

No significant performance differences were found between single- and dual-task conditions for the SA task or SART. However, participants did have significantly lower perceived SA in the dual-task, and higher subjective workload in the dual- compared to SA-alone task.

The results are largely as expected. Although it was predicted that a small performance decline would occur in SA performance in the dual-task situation, as Wickens (2002) suggests that a time-sharing requirement between tasks will result in some performance impairment, the minimal overlap in the present tasks' specific resource requirements on the MRT parameters is a likely reason for lack of statistically significant interference. The SA task utilized primarily audio and verbal processing, while SART is a visual-spatial task that requires little memory or planning. Thus, with no central executive bottleneck or overtaxing of specific resources, participants were actually able to dual-task relatively well in this experiment.

A previous dual-task study pairing SART and word recall saw significant performance declines in both tasks (Head & Helton, 2014b), but the performance declines in the present research failed to reach statistical significance. This may be due to the different cognitive demands of the SA compared to word recall task. The latter requires active rehearsal of unrelated words for rote recall, requiring constant working memory effort, whereas the scenario played for the SA task is listened to for the purpose of narrative recognition, and cannot be rehearsed. Though the SA task is mentally demanding, requiring language and narrative comprehension to the degree that sufficient situation details end up in episodic memory, participants were able to effectively manage the SART task on top of this demand without sacrificing performance. Alternatively, a lack of statistically significant interference could also be due to differences in the present SART task from the SART task used with the recall task mentioned above. The current SART task had a spatial separation of Go and No-Go stimuli, which may not only speed classification but also facilitate control of the prepotent tendency to respond. Recent research using the current SART task found the fastest reaction times and lowest commission errors of any recent SART task (A. Bedi, personal communication, May 2017), providing evidence that this task may have been easier than other SART versions. Perhaps if a task is easy enough (minimally cognitively demanding overall), no interference will occur regardless of specific mental resource requirements.

An additional possibility for why the SART task performance did not decline when dual-tasking is that task-relevant anxiety may *improve* response inhibition (Wilson et al., 2015). Because the dual-task inherently demanded more than either task alone along with a division of attention, the dual-task could have increased anxiety (or perceived load) and thus slightly improved one's ability to inhibit inappropriate responses (or increased effort) in the dual-task scenario. Kahneman cites arousal as a key component in the ability to mobilize additional mental resources (Kahneman, 1973). Thus, a dual-task performance decline and anxiety-based performance benefit could have cancelled each other out. However, this possibility is not put forth as the most likely explanation, due to the evidence that the SART task was easy and did not require response inhibition to the degree of other versions of the task.

Subjective workload when performing the SART task and dual-task were quite similar, with both being significantly greater than SA-alone workload. Though the SA task was rated an average of 38/100 on the workload scale by participants in this experiment, it did not seem to add to perceived workload when participants are already performing the SART task. This supports the idea that the SA task utilizes different, readily available resources that do not compete with the resources being used by the SART task. However, when the mental demand and frustration subscales were analyzed, it was revealed that the dual-task was more mentally demanding than the SART task alone, but the SART task was more frustrating. Having an additional goal of maintaining SA while performing SART may mitigate frustration without significantly impairing performance, at least in the specific conditions of this experiment.

The SA-SART dual-task interference was then compared to the SA-Quadra interference. From a superficial perspective, the SA task seems to require audio and verbal resources as well as language comprehension, while the Quadra and SART tasks require visual and spatial resources. However, as seen in Figure 9-1, Quadra significantly interfered with SA performance but SART did not. This cannot be explained by specific resource demand overlap (or lack thereof) alone. It was suggested in the discussion of Chapter 8 that the interference between SA and Quadra is likely due to one or two possible reasons. The first possibility is an executive resource overload or bottleneck (Quadra requires planning, a frontal process). The second possibility is that the SA task actually requires visual and spatial resources, on top of the audio and verbal resources. Because SART did not interfere with SA like Quadra did, the latter possibility can be mostly ruled out: if the SA task was actually visual-spatial in nature, performance should go down when paired with the SART task as well. Therefore, the interference between Quadra and SA is likely not due to the specific resource demand overlap, but the planning requirement that causes an executive resource bottleneck.

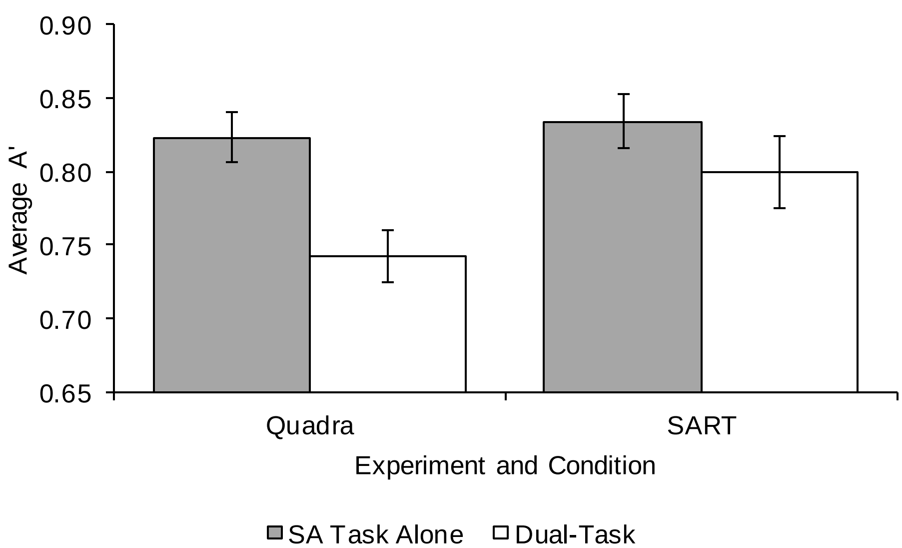

Figure 9-1. Average SA (A′) in the single- and dual-task in two experiments. Error bars are standard error.

Effect sizes (Cohen's d_z) for the interference between all SA task pairings to-date can be seen in Figure 9-2. Quadra's effect on SA is seemingly comparable to the effects of an outdoor running task and a semantic discrimination task. Though running does not require any overtly overlapping specific resources, it does require its own element of SA (e.g., track hazards, other environmental stimuli, one's physical status), which may be a partial cause of interference. The semantic discrimination task, on the other hand, requires verbal resources like that of the SA task. Having to read and classify rapidly appearing words is likely the major cause of interference when trying to listen to, comprehend, and remember a scenario. It is interesting that the Quadra task impedes SA nearly as much as the semantic task, emphasizing the importance of considering not only task-specific demands, but the overall executive demand of each task as well. It is important to note that similar levels of interference can occur for different reasons.

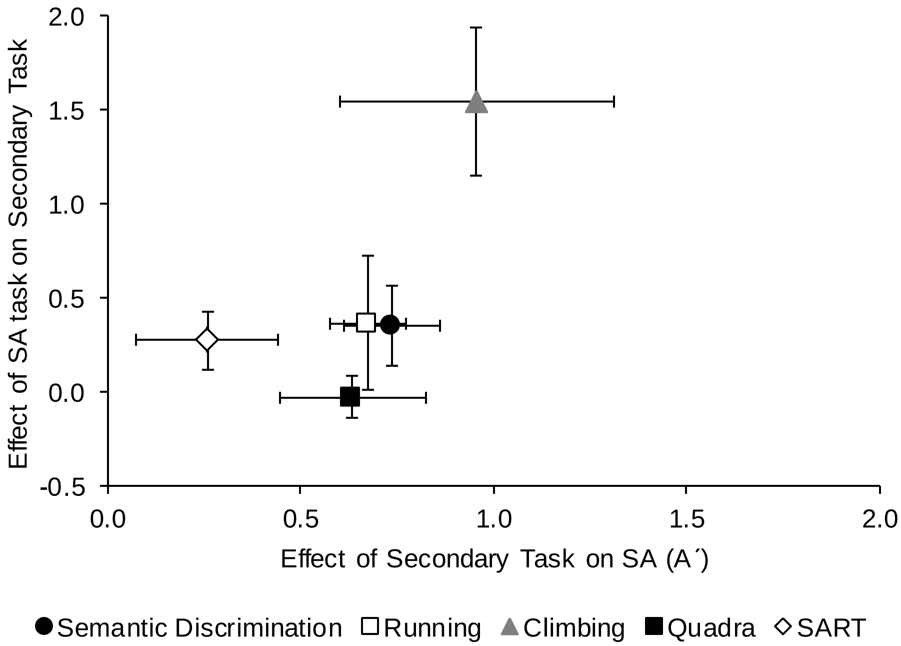

Figure 9-2. Standardized effect sizes (Cohen's d_z) for interference effect of different experimental tasks on SA (x-axis) and the interference effect of the SA task on those same experimental tasks (y-axis). The performance metric for the semantic discrimination task is proportion of hits, running is distance (meters), climbing is efficiency (holds per meter), Quadra is raw game score, and SART is errors of commission. Error bars are standard error of the mean for their respective dimensions.

The SART task, on the other hand, had similar dual-task performance decline as the running and semantic discrimination task. Though the running distance and SART errors did not decline significantly in the dual-task condition, the average relative decline was on par with that of the semantic discrimination task (i.e., still noteworthy). Though Quadra performance did not seem to decline at all, this may be due to a lack of sensitivity in research design rather than actual lack of interference.

Future research should look into the apparent lack of balance in dual-task performance decline, i.e., why performing certain tasks seem to impede SA more than maintaining SA impedes performance on the other tasks, or vice versa. For example, based on effect size alone, Quadra, running, and semantic discrimination have a greater negative impact on SA than SA has on them, whereas maintaining SA has a greater negative impact on climbing performance than climbing has on SA. Is this due to prioritization inconsistencies, or is it perhaps a further cognitive processing mystery? A multiple resource perspective points towards a lack of equivalent resource efficiency and different performance operating characteristics (Navon & Gopher, 1979). Shifting mental resources from Task A to Task B will not necessarily result in a performance improvement in Task B equivalent to the decline in Task A if the tasks do not require the same type of resources (Navon & Gopher, 1979). Thus, if diverting resources from one task to another with the hopes of optimal performance on both tasks harms the first task more than it helps the second, it does not make sense to divert resources at all. Future research should explore the cause of potential directional effects.

Though Wickens shows that utilizing a matrix of multiple resources provides better performance prediction power than a general resource pool on its own, he does not reject the importance of considering the executive resource demand of any task. Therefore, the present research – on its own, and in context with previous SA pairings – strongly supports his overall idea of considering both the executive resource requirements as well as the specific resources required of both tasks when predicting dual-task performance. Though a distinction between structural and capacity models of attention exists (Kahneman, 1973), Navon and Gopher (1979) elaborate on how neither perspective can account for all interference phenomena. Wickens' model does well to incorporate important aspects of both perspectives, as they do not have to be mutually exclusive. The importance of considering both the type of resources required and the present capacity of the system is supported by the results of the present research.

10 Comparative Analysis and General Discussion

The primary aim of this dissertation was to systematically examine the MRT, especially in the context of physically strenuous tasks. A secondary aim was to better understand the resource demands of certain applied tasks through a comparison of a variety of dual-task experiments. Chapters 2 to 9 are each self-contained studies with their own discussions and conclusions. The verbal recall studies build on one another, as do the SA studies, and the discussions found in each chapter include some inter-study comparisons (particularly Chapters 4, 7, and 9). Thus, this chapter will focus on novel comparisons across the recall and SA dual-task pairings, and the take-home messages of the body of work as a whole.

10.1 Verbal Recall versus Situation Awareness Interference Findings

In this dissertation, the verbal recall task was paired with a semantic discrimination task, running task, and puzzle task (Quadra). In previous research, this particular recall task has also been used in several climbing tasks, as well as a manual tracking task and SART task. A similar collection of experiments were then conducted with the recall task replaced by the SA task. The SA task was used in the same semantic discrimination, running, and Quadra tasks, and was also paired with a climbing task and SART task in order to make more comparisons across both dimensions of the dual-task design. Verbal recall paired with semantic discrimination might be expected to show very different interference effects than verbal recall and running interference (this hypothesis was supported by results), but would verbal recall paired with semantic discrimination interference effects be similar to those of SA paired with semantic discrimination? It could be argued that the recall and SA tasks both use verbal resources, an important dimension on Wickens' model, but are the tasks really that similar?

Kahneman (1973, p. 191) stated that, "Choices, decisions, rehearsal, and the mental manipulation of stored symbols, all appear more demanding than routine perceptual analysis." This is especially true when there is time pressure on a given task - the rate of cognitive processing is often a major determinant of required effort. Some tasks allow for a mental rest, meaning people are able to 'take it easy' by slowing down the rate of processing or easing off on their mental effort. Other types of tasks inherently impose a demanded rate that does not allow for reducing mental effort. Kahneman (1973, p. 191) said that "this is especially true of any mental act that depends heavily on short-term memory, since the rate of rehearsal must compensate for the rate of decay of stored information." Though the SA task requires continuous listening and processing of verbal inputs, the recall task requires constant rehearsal of words (or mnemonics) in order to do one's best. The former is more of a narrative or episodic memory task, requiring thoughtful processing and integration but not allowing for rehearsal. It is better to listen to the scenario as a whole than attempt to rehearse certain details of it verbatim, because the latter likely does more harm than good by preventing focused listening to the rest of the scenario. The word recall task involved rote recall with time pressure, requiring constant mental effort: if one wants to do well, there is no choice but to constantly rehearse the words, at the fastest rate possible. In addition, participants are aware in advance that the words in the recall task must be freely recalled, while the SA task only requires recognition memory on a true/false assessment, perhaps leading to differential levels of effort.

Though the experimental design was the same, the SA and word recall results cannot automatically be compared, as the performance metrics are not the same. In order to make comparisons across studies, standardized effect sizes for dual-task performance decline in both tasks were calculated for every experiment in this dissertation, along with a few recent works that utilized the same verbal recall task. The SART/Word Recall results come from Head and Helton (2014b), and the Climbing/Word Recall results come from pooled data - Green and Helton (2011) and Green and colleagues (2014). All other effect sizes come from the experiments in this dissertation. Performance effects in the recall and SA tasks can be seen in Table 10-1 and performance effects of concurrent recall or SA on all of the other tasks can be seen in Table 10-2.

Table 10-1. Dual-task performance decline in word recall and SA as a function of concurrent task

	Response Task	
Criterion Task	Word Recall	Situation Awareness
Semantic Discrimination	1.271(.192)	.737(.214)
Quadra	1.609(.231)	.634(.189)
SART	.757(.207)	.258(.185)
Running	.699(.247)	.676(.360)
Climbing	2.292(.369)	.956(.399)

Note. Standardized effect sizes (Cohen's d_z) and standard error for interference effects (performance in dual-compared to single-task) of different dual-task pairs.

Table 10-2. Dual-task performance decline in various tasks as a function of concurrent recall or SA task

	Criterion Task	
Response Task	Word Recall	Situation Awareness
Semantic Discrimination (prop.hits)	.866(.123)	.352(.125)
Quadra (score)	.118(.118)	-.032(.111)
SART (EoC)	.456(.217)	.272(.158)
Running (distance)	.367(.112)	.364(.098)
Climbing (distance)	.652(.117)	.537(.181)

Note. Standardized effect sizes (Cohen's d_z) and standard error for interference effects (performance in dual-compared to single-task) of different dual-task pairs.

As seen in Figure 10-1, SA performance seems to be harmed less by dual-tasking than word recall in all of the different scenarios (though the difference in effect sizes is minimal in the running task).

This is consistent with Kahneman's explanation of the difference between tasks requiring 'routine perceptual analysis' and tasks requiring rehearsal and time pressure. Although remembering words is not inherently more 'difficult' than remembering details of a story, the results provide evidence that the former is more cognitively demanding – at least within the parameters of these experiments. Due to the fact that the SA task does require constant focus, language comprehension, and situation updating, this is a somewhat surprising and important result. In addition, the biggest relative differences in the dual-tasking interference effects on word recall versus SA are when the secondary tasks require planning (Quadra and climbing). The results suggest that it may be more difficult to listen and rehearse simultaneously (as in the case of the word recall task) than it is to listen without a need to rehearse (in the case of the SA scenario), particularly when performing a simultaneous secondary task that requires planning. If a second task requires more of the limited working memory capacity for planning (or other) requirements, it leaves little free processing power. Diminished working memory capacity, due to the reasons mentioned above, thus harms words recall more than it harms scenario memory.

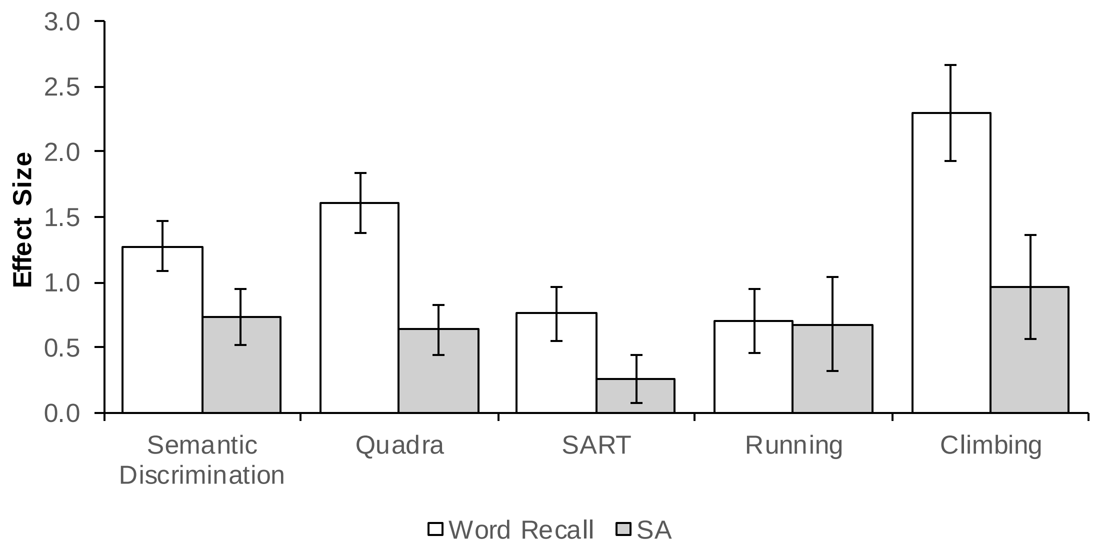

Figure 10-1. How dual-tasking with various secondary tasks affects recall and SA performance. Standardized effect sizes are Cohen's d_z and error bars are standard error.

As seen in Figure 10-2, the recall and SA tasks seem to interfere with the secondary tasks in a somewhat consistent fashion, though maintaining SA seems to have a lesser effect overall. Perhaps the episodic buffer (Baddeley, 2000) is very efficient in handling the requirements of maintaining SA, keeping other resources available and processing mechanisms free. The central executive may be required to drive the rehearsal of words, but not required for listening in the SA task. In addition, people are more practiced at processing and understanding the events unfolding around them, so it is more natural for people to comprehend and remember a narrative scenario than rehearse and remember a random string of words.

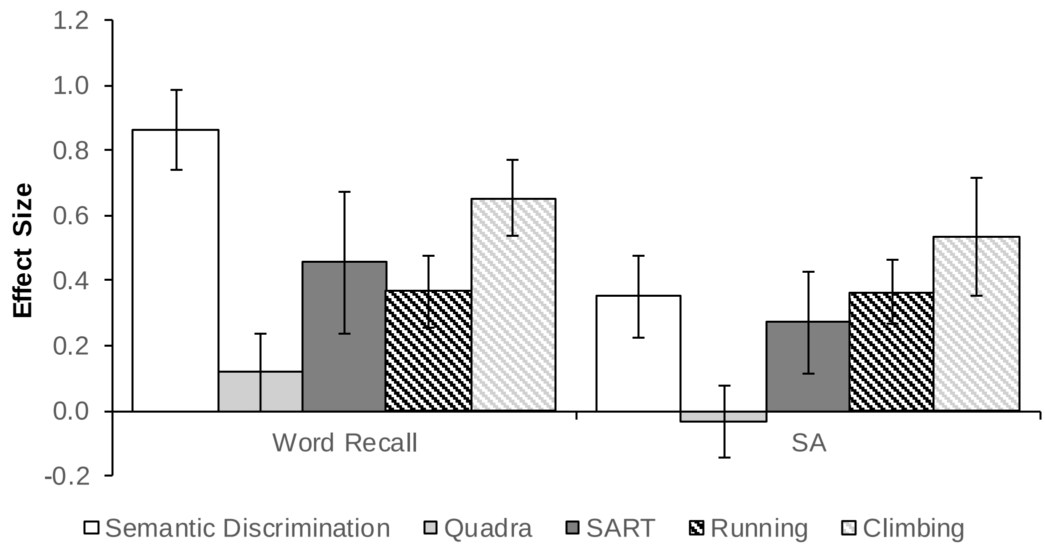

Figure 10-2. How dual-tasking with word recall and SA affect all of the other tasks examined. Standardized effect sizes are Cohen's d_z and error bars are standard error.

Neither remembering words nor maintaining SA significantly harmed Quadra performance (see Chapters 4 and 8 for potential limitations of this result). It seems as though it is notably more difficult to perform the semantic discrimination task while remembering a list of words than while remembering a scenario, and as seen in Figure 10-1 it was also harder to remember words than the scenario while performing the semantic discrimination task. This lends support to the idea that though the scenario is presented verbally, perhaps the SA task does not rely as heavily on verbal resources as the recall task (listeners must absorb the information from the scenario verbally, but perhaps they process it spatially by visualizing rather than rehearsing the scenario). It is also shown that climbing distance was harmed by both tasks. The effect on climbing efficiency (holds per meter) in the SA task was even greater than the effect on distance (see Chapter 7), but not all of the required data to compute the effect size for the efficiency metric for the previous climbing-recall experiments could be obtained. Thus, the distance metric was chosen for comparison purposes. Efficiency, however, is likely a more realistic performance metric to consider, particularly because it is essential that search and rescue climbers conserve energy wherever possible. In addition, speed and distance are usually not as important as choosing the best path from point A to B.

It should be noted again that all participants in all experiments were told to do their best on both tasks in the dual-tasking condition – they were not supposed to prioritize one task over the other. One can see in Figure 10-1 that the climbing task interferes with word recall more than the semantic discrimination task does. However, when looking at Figure 10-2, it is seen that attempting the word recall task harms semantic discrimination performance more than it does climbing. Despite an overlap in resource demand with the semantic discrimination task, it is actually harder to remember words when faced with a multifaceted task like climbing that requires a mixture of resources (executive and otherwise) that still have not been pinpointed. On the other hand, the recall task does not harm the climbing task as much as the discrimination task. This cannot be easily explained without more research, but highlights the message that climbing is a unique task that needs to be better understood.

Cowan (1988) suggested that more information may be retained when it is divided between two or more modalities. Working memory is likely limited by overall capacity, but may also have separate limits for the different entities of the complex system. Because the SA task can potentially be split between visual-spatial and verbal memory systems, perhaps this is another reason why SA performance tends to decline less when dual-tasking than does free recall of words. Cowan (1988) also stated that rehearsal, problem solving, and integration or recombination of short and long term memory units are information transfer operations that load the central executive. This may explain why Quadra and climbing interfere more with verbal recall and SA than do running and SART – the latter two tasks do not seem to demand as much of the central executive as the former.

10.2 Future Research

There are truly countless ways to expand upon this research; the matrix of dual-task pairs would be easy to grow in both width and length. With the specific target of military, firefighting, search and rescue, police, and other physically strenuous, high-risk domains, swimming tasks could be incorporated to better understand the demands on rescue divers, orienteering and trail running tasks to target army scouts, and wayfinding and vertical climbing tasks would provide a more realistic task for search and rescue climbers. It would be particularly useful to insert a physical task that requires the same degree of full-body exertion as climbing, but with different perceptual, processing, and response requirements. Virtual reality could also be used to have participants experience the same cognitive demands of certain physical tasks without the actual physical component. A variety of cognitive tasks could also be inserted into military, firefighting, EMS, and other types of training exercises to ascertain realistic effects.

A better understanding of dual-tasking interference would also be very useful in competitive athletics. Most sports require physically strenuous processes (that may or may not have their own executive demand) concurrently with decision making, strategizing, remembering set plays, and other cognitive processes. A better understanding of the interference of mental and physical activities could be used to enhance performance in a variety of ways. Swimming, rowing, boxing, karate, mountain biking, and countless other tasks would easily slot into this dual-task paradigm.

Several other tasks would help to better explore the different types of cognitive resources available. The verbal recall and SA tasks could be presented in a different modality, for example, a head up display could be used to present the words and a visual dramatization of the SA scenario. Word or object search tasks, spatial vigilance tasks, and spatial recall tasks would help explore different areas of Wickens' cognitive resource matrix. N-back working memory tasks, where participants monitor a sequence of stimuli and have to decide whether the current stimulus is the same is the stimulus presented N-steps earlier in the sequence, could be used to easily manipulate not only the difficulty level of a task (i.e., increase or decrease N), but also the verbal versus spatial demand (i.e., the stimuli could be words or shapes), visual versus auditory demand (i.e., the stimuli could be presented on a screen or through headphones), et cetera. A Lego-building task could be used to further test the use of planning and tactile manipulation of objects, while a hand ergonometer task would add to the physical task collection to test the interference when the upper limbs alone are used, with minimal planning requirements. Mental arithmetic tasks would also be interesting to explore in comparison to word recall.

In addition to just adding to the breadth of dual-tasking pairs, research with different difficulty levels for tasks, or different task prioritization instructions would also be useful. Kahneman stated that people have "considerable freedom to determine which task will suffer interference. Subjects are capable of protecting one task, so that it is performed in conjunction with another nearly as well as in isolation." (Kahneman, 1973, p. 200). Manipulation of the timing of events could also prove useful, in order to better understand where in the processing stage the interference occurs. Performance measures could also be collected throughout the duration of the task, rather than just at the end. The principle of graceful degradation suggests that performance declines proportionally to the resource depletion over time (Norman & Bobrow, 1975). Thus, performance deficits towards the end of the task may far outweigh those in the beginning of the task when resource stores are still full, and performance measures should have greater sensitivity to account for this.

There has been research showing people can become better at dual-tasking over time, even when the MRT would predict the tasks to be nearly impossible to perform concurrently. For example, after plenty of practice, people were able to read short stories while simultaneously writing and even categorizing dictated words without sacrificing reading speed or comprehension (Spelke, Hirst, & Neisser, 1976). This may seem inconsistent with the idea that people have limited specific resources, but practice can decrease the actual demand of each task, or improve time-sharing ability. The acquisition of dual-tasking expertise would be an interesting future direction for this research as well.

10.3 Conclusion

When studying the cognitive resource structure through dual-task interference, there is great utility in holding one task constant across a variety of dual-task pairings. In this collection of work, the word recall task was held constant across a semantic discrimination task, running task, and puzzle task (there were several additional studies already available for comparison). Then, many of the dual-task pairs were repeated using the newly developed SA task in place of the recall task. The goal was in part to better understand the specific resources required by each task, but this goal was to a lesser extent than that of understanding the dual-task interference in context with other dual-task pairings. In this dissertation, the MRT was systematically explored with a variety of interfering and non-interfering tasks in a more applied context.

This collection of work examined physically strenuous tasks both with and without planning requirements, physical tasks with and without verbal requirements (if the notion that climbing utilizes internal verbal planning is upheld), seated tasks with and without verbal requirements, seated tasks with and without planning requirements, and how they all interfered with the semantic (free recall) and episodic (SA task) verbal tasks that were held constant. Effect size computations allowed for comparisons across studies, and 2-dimensional graphical representations of interference. In Figure 4-3 and Figure 9-2 in particular, it can be seen that climbing is uniquely challenging in comparison to other tasks that were paired with the verbal free recall task as well as the SA task. This is new information and has implications for both the understanding of resource theories and how they should be applied to real dual-tasking situations. According to this research, the interference between two simultaneous tasks required of operators must be thoroughly assessed rather than assuming the level of interference that might occur simply based on theories that are currently available. The MRT seems to withstand systematic testing, but without a better understanding of the tasks themselves, it cannot be easily applied. There is also evidence that a revision of the MRT structure to allow for physical tasks and a central executive bottleneck would perhaps provide for a better all-encompassing prediction tool.

One novel feature of this program of work is that climbing appears to be uniquely demanding (Figure 4-3, Figure 9-2). This is not an obvious finding; it is suspected that many psychologists would assume a verbal recall task paired with a semantic discrimination task would be more interfering than a verbal recall task paired with climbing. The fact that Quadra, which requires planning, interfered with verbal recall but not at the cost of Quadra performance again suggests there is something more to the interference in climbing than simply the requirement to plan. Consider an application of this work, such as the climbing required in search and rescue or firefighting. A current practitioner may read something like Wickens' MRT and assume climbing would not interfere greatly with verbal recall - on the surface climbing seems a non-verbally demanding task. The present research suggests this is an incorrect and potentially dangerous assumption. The cognitive demands of ecologically relevant physical activity may at present be seriously underestimated, or in the very least misinterpreted. Remember, most research examining dual-task interference of physical tasks up until this point has used stationary cycling or treadmill running, which as noted is not representative of the demands of trail running and off-road cycling and less so of occupations such as firefighting, warfare, and search and rescue where physical effort is paired with cognitive demand. Even the physical tasks used in this dissertation only inch somewhat closer toward representing the real-world activities. Trail running and outdoor climbing with navigation components would be more representative, but this work serves as a stepping stone and highlights the true need for further research. This research may also have implications for understanding of the evolution of cognition generally.

A better understanding of dual-tasking abilities and patterns of interference is important in any domain aiming to improve worker efficiency and productivity. But beyond that, there are greater potential benefits to be reaped in the domain of physically demanding, high-risk jobs. The military, police, search and rescue climbers or divers, firefighters, and various other people that put their lives on the line every day have to dual-task frequently, one of the tasks often being a strenuous and dangerous physical task. By figuring out the best ways for operators to attend to incoming information and execute higher order thinking necessary to fulfill their mission, while simultaneously fulfilling the physical demand, the coexistence of individual tasks can be better manipulated to make the operators safer, more efficient, and overall better at completing their mission.

Though there is ample evidence supporting the MRT, and alternatively, evidence supporting a unitary resource structure as well, this research implies that it is not only possible, but perhaps likely, that both viewpoints are in part correct. Though the *type* of resources used in different tasks are important predictors of interference (MRT), the overall *amount* of demand (central capacity model), particularly demand on the central executive, is important as well. For example, two tasks requiring the same resources on Wickens' model will interfere more than two that require different resources, however among the former, they will interfere even *more* if one or both of the tasks require planning. A task like climbing may even cause a level of interference that can be fully explained by neither specific resources *nor* planning requirements. In conclusion, this research provides general support for the MRT, but with certain caveats. The importance of assessing all task demands individually before making assumptions about the capability of operators to perform them simultaneously has been highlighted, as certain tasks may be far more demanding, and demanding in different ways, than would be assumed given the MRT. It is important to recognize that task demands may not be obvious, and physical strain may impair cognitive performance in its own way. Continuing this research using new real world, operationally relevant tasks is suggested, with the goal of better advising which tasks should (or should not) be placed on an operator at a given time, and how to better mitigate interference when the interference is expected but dual-tasking is unavoidable.

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Appendix A. Word Recall Lists

Word Recall List 1:

Ankle, banner, bullet, cowhide, doorman, hostage, icebox, infant, leopard, locker, missile, monarch, mucous, piano, pudding, saloon, slipper, sulphur, sunburn, thicket

Word Recall List 2:

Bandit, blister, butcher, fabric, fiord, harness, jelly, lobster, morgue, nectar, pepper, piston, rattle, reptile, salad, settler, singer, sultan, trumpet, typhoon

Appendix B. VO_2max Models

Participants' VO_2max was estimated using the two models below.

The 1-mile Jog Test (George, Vehrs, Allsen, Fellingham, & Fisher, 1993):

Test procedure: The biographical details collected from the participant, along with their self-ranking on the activity scale below, was plugged into the formula VO_2max^1 = 100.5 + (8.344*gender) – (0.0744*weight) – (1.438*mile time) – (0.1928*heart rate), where gender is coded 1 for male, 0 for female, weight is given in pounds, the mile time is in minutes and fraction of minutes (e.g., 14:30 = 14.5 minutes), and the heart rate is taken immediately following the 1-mile jog.

The Jackson Non-Exercise Test (Jackson et al., 1990)(Jackson et al. 1990):

Test procedure: The biographical details collected from the participant, along with their self-ranking on the activity scale below, was plugged into the formula VO_2max^2 = 56.363 + (1.921*PA-R) – (0.381*age) – (0.754*BMI) + (10.987*gender), where gender is coded 1 for male, 0 for female, and BMI is weight (in kilograms) divided by height (in meters) squared.

Participant Activity Rating (PA-R):
CIRCLE the appropriate number (0 to 7) which best describes your general activity level for the previous month.

Category 1. Do not participate regularly in programmed recreational sport or heavy physical activity.

0 – Avoid walking or exertion, e.g., always use elevator, drive whenever possible instead of walking.
1 – Walk for pleasure, routinely use stairs, occasionally exercise sufficiently to cause heavy breathing or perspiration.

Category 2. Participated regularly in recreation or work requiring modest physical activity, such as golf, horseback riding, calisthenics, gymnastics, table tennis, bowling, weight lifting, yard work.

2 – 10-60 minutes per week.
3 – Over one hour per week.

Category 3. Participate regularly in heavy physical exercise such as running or jogging, swimming, cycling, rowing, skipping rope, running in place or engaging in vigorous aerobic activity-type exercise such as tennis, basketball, or handball.

4 – Run less than one mile per week or spend less than 30 minutes per week in comparable physical activity.
5 – Run 1 – 5 miles per week or spend 30 – 60 minutes per week in comparable physical activity.
6 – Run 5 – 10 miles per week or spend 1 to 3 hours per week in comparable physical activity.
7 – Run over 10 miles per week or spend over 3 hours per week in comparable physical activity.

Appendix C. NASA-Task Load Index (TLX)

Figure 8.6

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Appendix D. Subjective Stress State Questionnaire

For the following items use the response scale below the item by circling the vertical line closest to your answer; the scale goes from 0 (**very low**) to 100 (**very high**). These questions refer to you experience during the task.

1. **Mental Demand -** How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)?

   0 25 50 75 100

2. **Physical Demand -** How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)?

   0 25 50 75 100

3. **Temporal Demand -** How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred?

   0 25 50 75 100

4. **Emotional Demand** – How emotionally demanding was the task?

   0 25 50 75 100

5. **Performance Monitoring Demand** – How much did the task require you to monitor your performance?

   0 25 50 75 100

6. **Effort** – How hard did you have to work to accomplish your level of performance?

   0 25 50 75 100

7. **Physical Fatigue** – How physically exhausted and tired did you feel?

   0 25 50 75 100

8. **Mental Fatigue** – How mentally exhausted and tired did you feel?

   0 25 50 75 100

9. **Tense** – How tense or anxious did you feel?

   0 25 50 75 100

10. **Unhappy** – How unhappy did you feel?

0 25 50 75 100

11. **Motivation** – How motivated were you to do well?

0 25 50 75 100

12. **Task Interest** – How interesting was the task?

0 25 50 75 100

13. **Self Related Thoughts -** How much did you think about yourself?

0 25 50 75 100

14. **Concentration** – How focused on the task were you?

0 25 50 75 100

15. **Confidence** – How confident were you during the task?

0 25 50 75 100

16. **Task Related Thoughts -** How much did you think about the task?

0 25 50 75 100

17. **Task Unrelated Thoughts** – How much did you think about something other than the task?

0 25 50 75 100

Appendix E. Further Analyses - Chapter 4

Due to the large variation in Quadra performance, participants were stratified into two groups of 25 based on rank ordered Quadra scores. When the scores were ordered based on the average score of the dual- and single-task games, the lower scoring half of participants experienced a significantly higher percentage of information loss (i.e., remembered significantly fewer words in the dual- compared to single-task condition; $M = 50.4$, $SD = 21.6$), than the upper half did ($M = 34.5$, $SD = 24.8$), $t(24) = 2.50$, $p = .020$, $M_{\text{difference}} = 16.0$ (95% CI [2.8,29.1]). This also held true if the Quadra scores were ordered by performance in the dual-task alone ($p = .014$), and was nearly significant when scores were ordered by performance in the single-task alone ($p = .065$).

When Quadra scores were sorted based on the single-task score, the higher scoring half of participants had a significantly higher score in the single-task ($M = 10670$, $SD = 3663$) than the dual-task ($M = 8809$, $SD = 4891$), $t(24) = 2.23$, p = .035, $M_{\text{difference}} = 1861$ (95% CI [142,3581]). The lower scoring half of participants tended to score higher in the dual-task ($M = 4510$, $SD = 3226$) than the single-task ($M = 3544$, $SD = 1467$), though this difference failed to reach significance, $t(24) = 1.70$, $p = .103$, $M_{\text{difference}} = 966$ (95% CI [-210, 2142]). When scores were sorted based on the dual-task score, conversely, the high scoring participants tended to do better in the dual-task condition ($M = 10320$, $SD = 3841$) than the single-task ($M = 9093$, $SD = 4255$), although this difference failed to reach significance, $t(24) = 1.95$, $p = .063$, $M_{\text{difference}} = 1228$ (95% CI [-71,2527]). The low scoring participants did significantly better in the single-task condition ($M = 5122$, $SD = 3963$) than the dual-task ($M = 2999$, $SD = 1134$), $t(24) = 2.85$, $p = .009$, $M_{\text{difference}} = 2123$ (95% CI [585,3661]). A median split based on participants' average score in the two conditions revealed no significant differences.

Based on the stratified average Quadra scores, there was no significant difference in workload in the dual-task between the high performers ($M = 57.7$, $SD = 11.9$) and the low performers ($M = 60.0$, $SD = 11.9$), $t(24) = .60$, $p = .554$, $M_{\text{difference}} = 2.1$ (95% CI [-5.0,9.2]). There was also no significant difference in workload in the Quadra-alone task between high performers ($M = 31.7$, $SD = 13.5$) and low performers ($M = 38.1$, $SD = 14.3$), $t(24) = 1.63$, $p = .117$, $M_{\text{difference}} = 6.4$ (95% CI [-1.7,14.5]).

The large variation in Quadra scores could be one of many reasons why no significant dual-task effects were found. The analyses on the stratified data, described above, unfortunately did not lead to more compelling findings. Inconsistent results based on whether participants were ranked by dual- versus single-task Quadra scores do not allow strong conclusions to be made about different task prioritizations, strategies, or differential dual-tasking ability between those that are more versus less adept at Quadra.

Appendix F. Further Analyses – Chapter 8

Due to the large variation in Quadra performance, a median split was performed on Quadra scores for further analysis. There were no significant findings when the median split was performed based on the ranking of average score, or on the single-task score. However, performing a median split based on dual-task scores results in a significant difference in the poor performers' single- (M = 4015, SD = 2517) versus dual-task scores (M = 3168, SD = 1579), $t(24) = 2.084$, $p = .048$, $M_{\text{difference}} = 847$ (95% CI [8, 1686]).

The significant difference between dual- and single-task scores among the lower performers is consistent with previous research showing that those with more expertise are better able to handle additional task demands (Schaefer, 2014). In other words, any dual-task interference effects only impede Quadra performance in those that are less adept with the game in the first place. Unfortunately, the stratified data should be interpreted very cautiously, as the counterbalance can no longer be guaranteed.

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